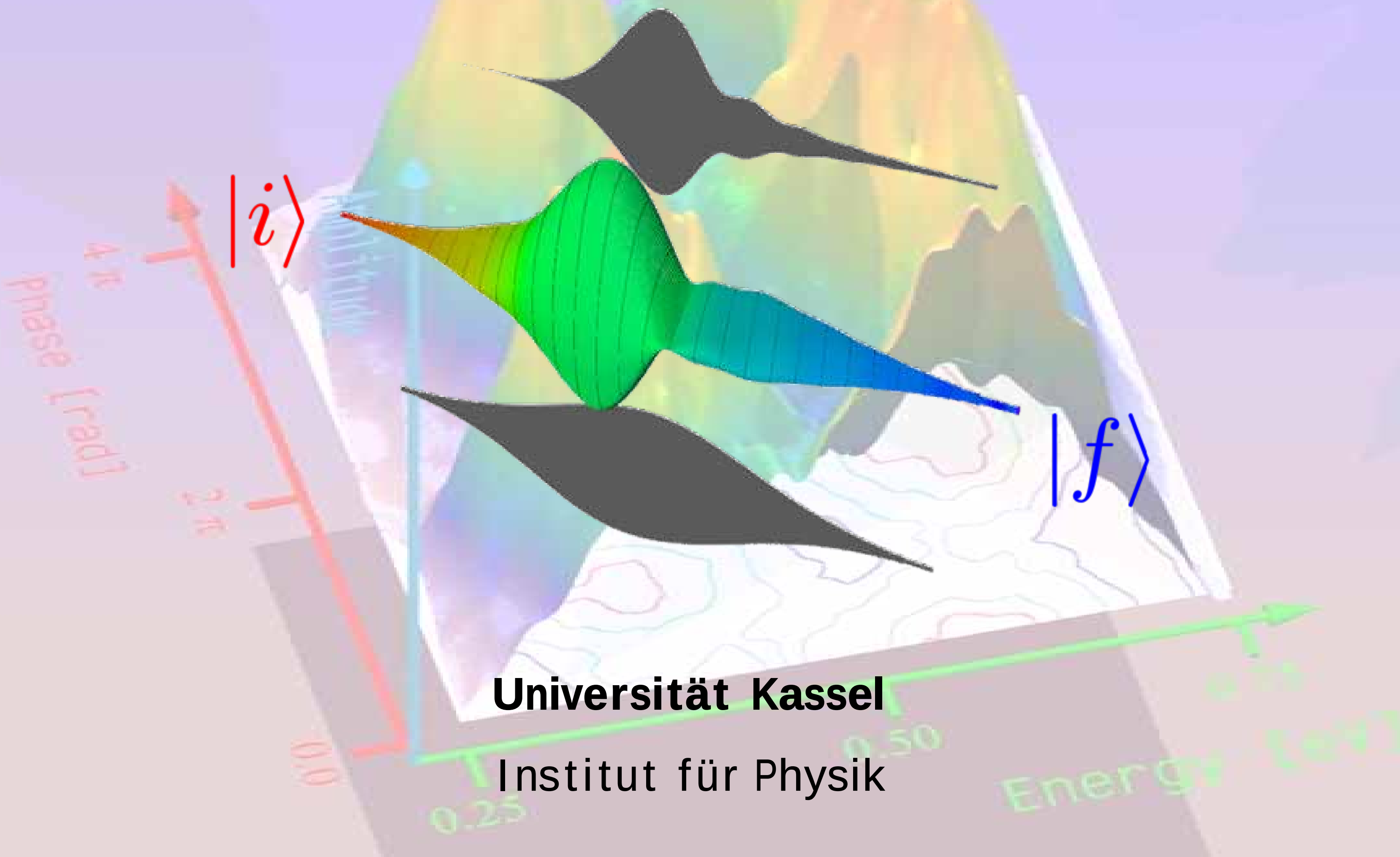
Creation, shaping and characterization of femtosecond laser pulses

M. Wollenhaupt and T. Baumert

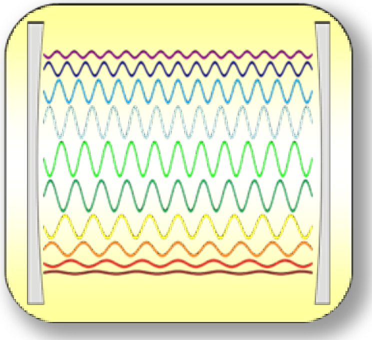


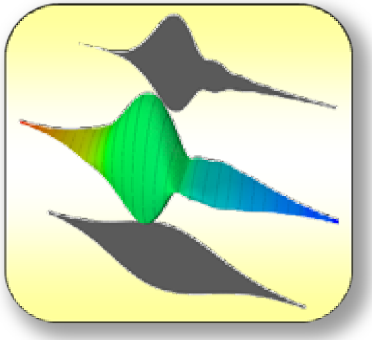
Universität Kassel

Institut für Physik

Outline

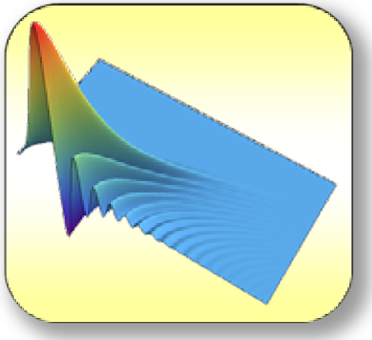
Generation
Laser modes
Mode locking
Pulse amplification



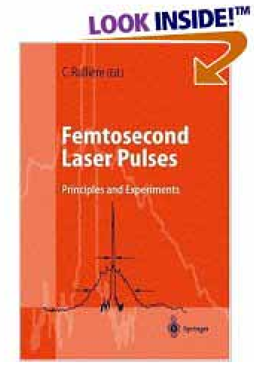


Manipulation
Dispersion in optical systems
Mathematical description
Pulse shaping

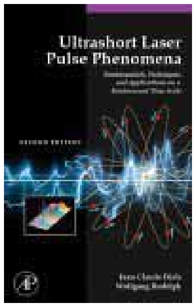
Measurement
Time domain
Frequency domain
Joint time frequency domain



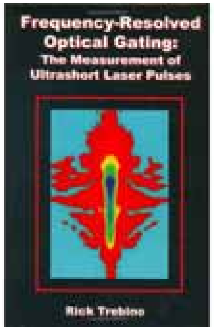
Literature



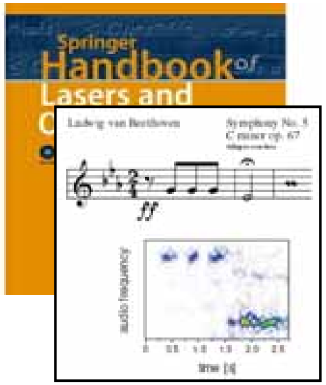
Femtosecond Laser Pulses (second edition)
Claude Rulliere, Springer 2004



Ultrashort Laser Pulse Phenomena (second edition)
Jean-Claude Diels and Wolfgang Rudolph, Academic Press 2006



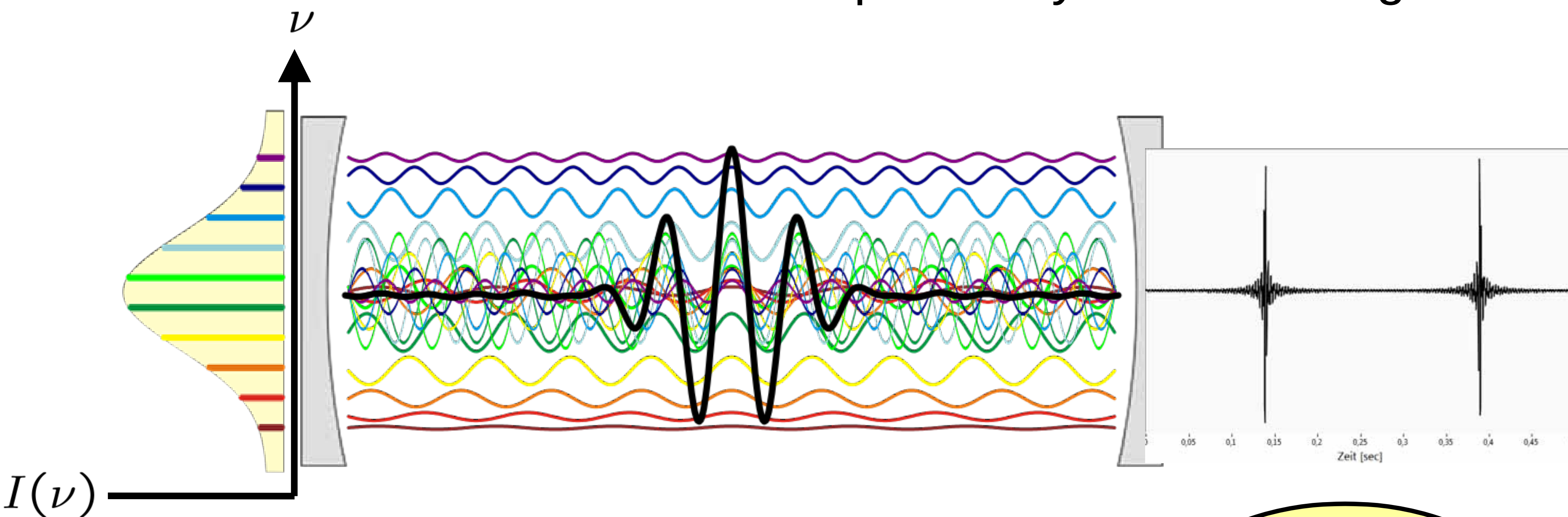
Frequency-Resolved Optical Gating
Rick Trebino, Kluwer 2002



Springer Handbook of Laser and Optics, Chap. 12
Femtosecond Laser Pulses: Linear Properties, Manipulation, Generation and Measurement,
M. Wollenhaupt, A. Assion and T. Baumert, Springer 2007

(available from our homepage ***physik.uni-kassel.de/index.php?id=exp3****)*

Generation of ultrashort laser pulses by mode locking

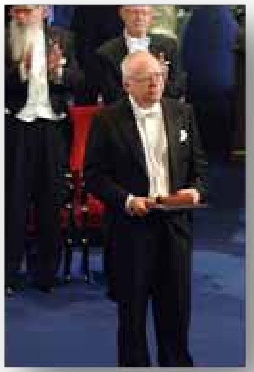


Longitudinal laser modes

$$L = n\frac{\lambda_n}{2}$$

$$\nu_n = n\,\frac{c}{2L}$$

Theodor W. Hänsch



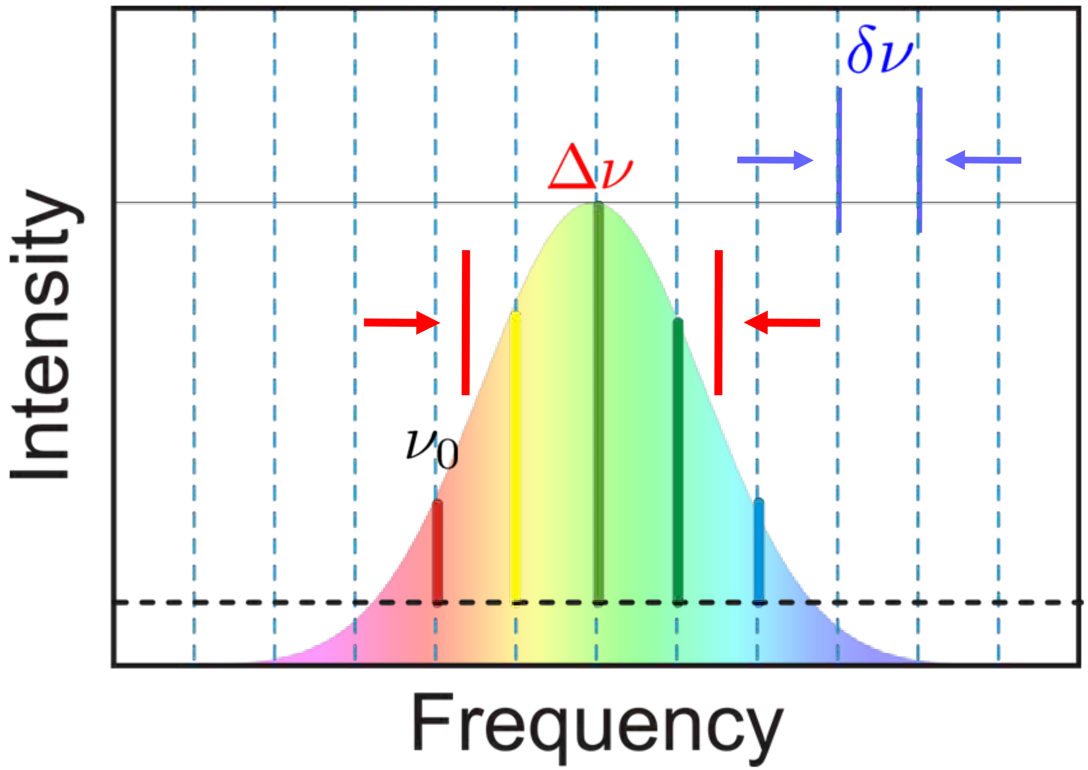
John L. Hall

Frequency comb

Longitudinal laser modes in frequency domain

$$\nu_n = n\,\frac{c}{2L}$$

$$\delta\nu = \frac{c}{2L}$$



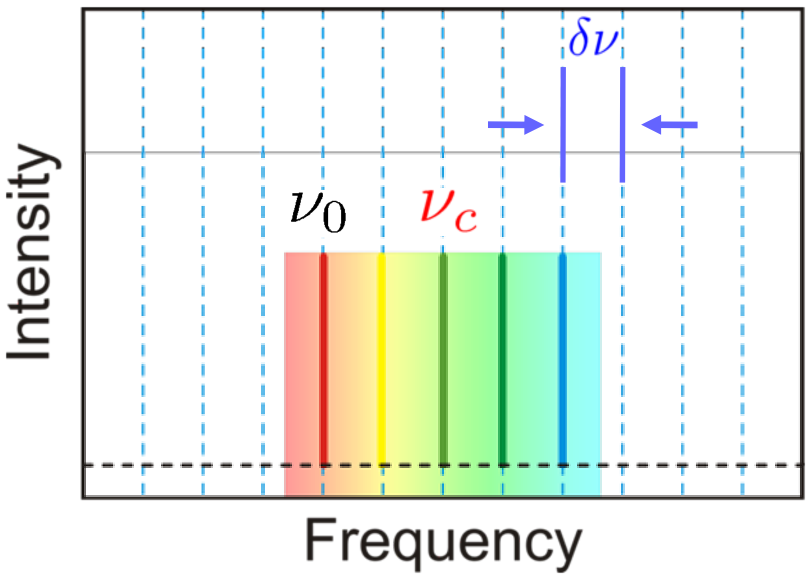
$\Delta\nu$ gain bandwidth $\approx N \cdot \delta\nu$

$$E_n(t) = A_n \sin\left\{2\pi\left[\nu_0 + n\,\delta\nu\right]t + \phi_n(t)\right\}$$

Mode locking quantitatively

Single mode: $E_n(t) = E_0 \sin\{2\pi\,[\nu_0 + n\,\delta\nu]\,t\}$

Simple case:



$$E(t) = \sum_{n=0}^{N-1} E_n(t)$$

$$A_n = E_0$$

$$\phi_n = 0$$

$$E(t) = E_0 \sum_{n=0}^{N-1} \sin\left(2\pi\,[\nu_0 + n\,\delta\nu]\,t\right)$$

$$E(t) = E_0 \sin\left(2\pi\nu_c\,t\right)\cdot\frac{\sin(\pi N\delta\nu\,t)}{\sin(\pi\delta\nu\,t)}$$

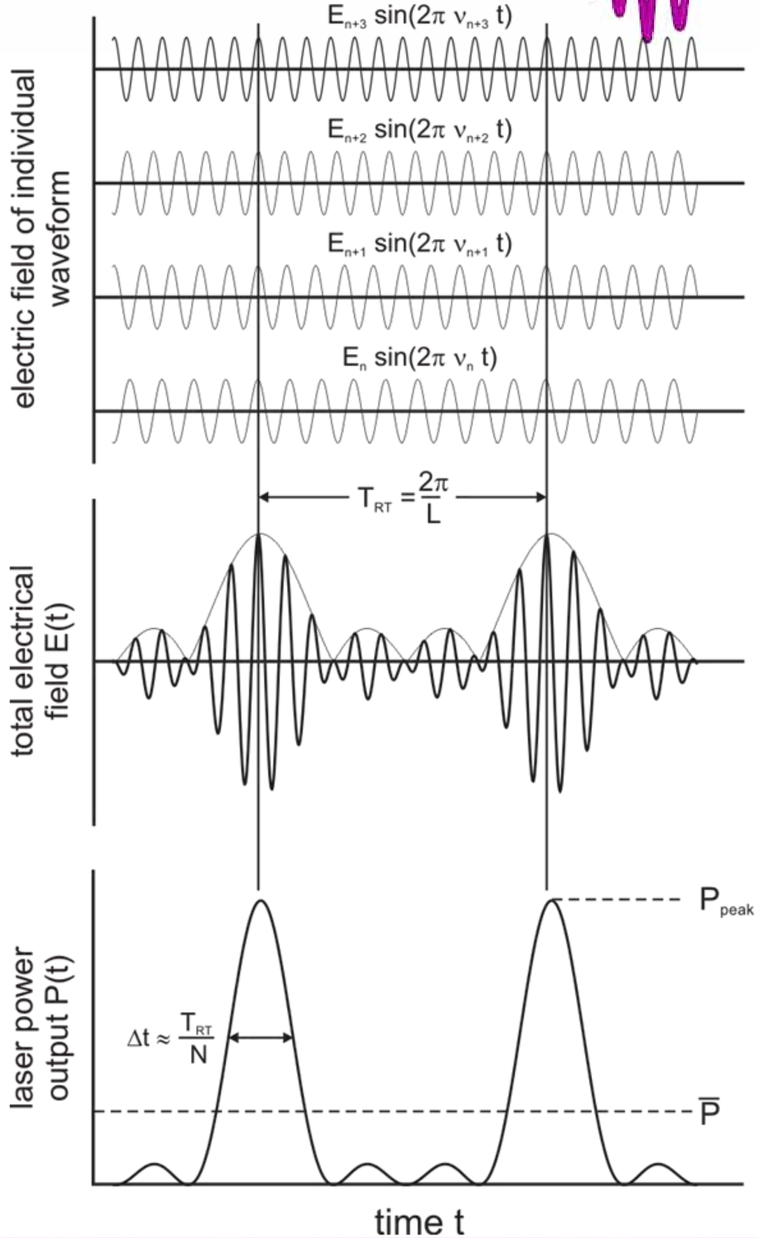
Example: four modes

$$I(t) \propto \frac{\sin^2(\pi N \delta\nu\, t)}{\sin^2(\pi \delta\nu\, t)}$$

$$P_{Peak} = N^2 P_0$$

$$< P >= N P_0$$

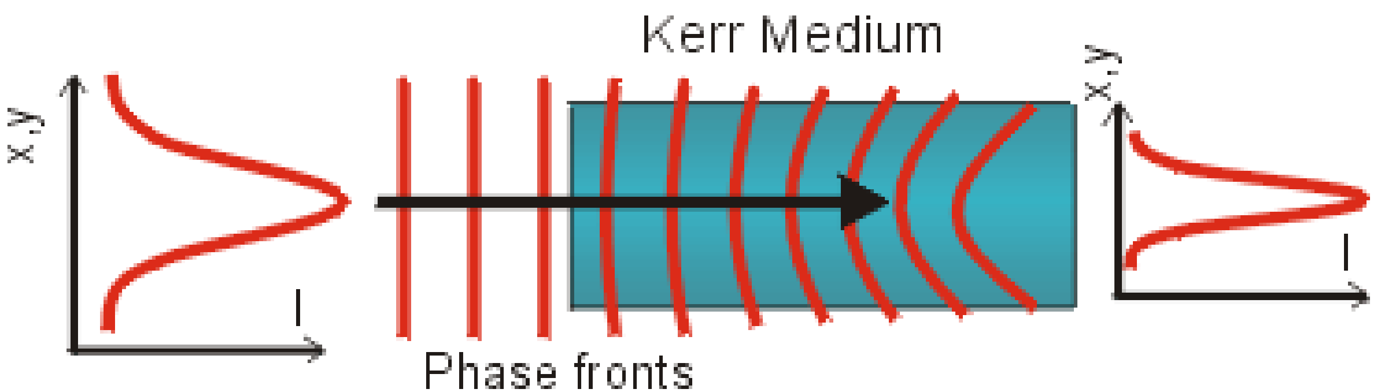
$$\Delta t \approx \frac{T_{RT}}{N} = \frac{1}{N\delta\nu} = \frac{1}{\Delta\nu}$$



Passive mode locking with Kerr lens

At high intensities, the index of refraction is getting intensity dependent

$$n(x,y,t) = n_0 + n_2\, I(x,y,t)$$



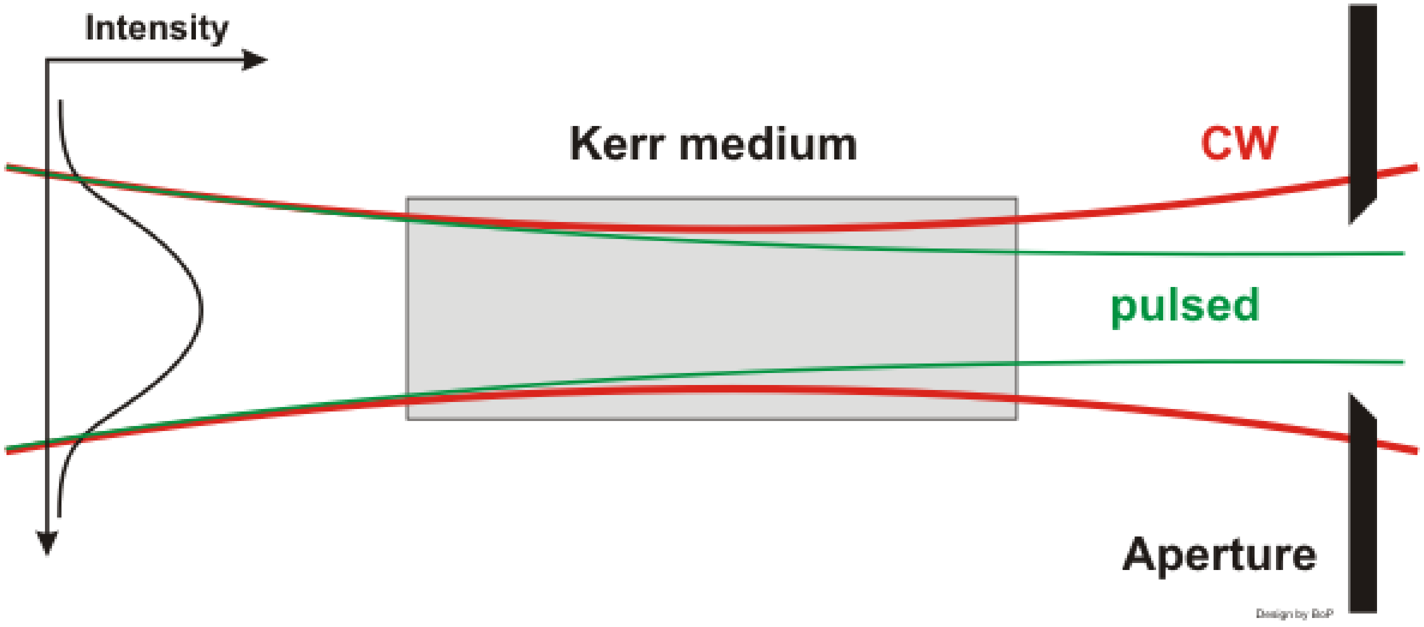
The Kerr lens generates self focussing

The spatial intensity distribution of the laser beam together with a Kerr nonlinearity establishes a KERR LENS

Passive mode locking with Kerr lens

For low intensity cw beams: No Lens effect

For high intensity pulsed radiation: Kerr Lens



An aperture yields high losses for cw and low losses for pulsed operation

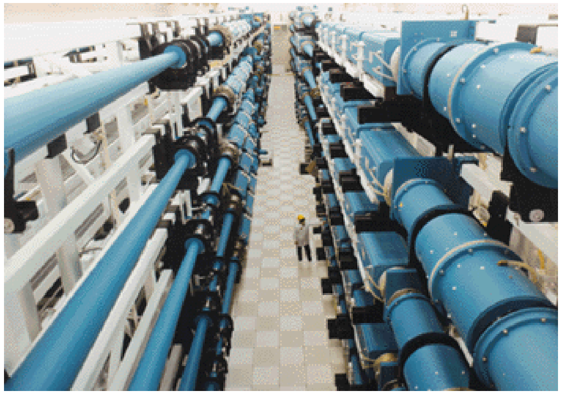
Pulse amplification

Problem: High intensities! (self focusing followed by destruction)

$$Power = \frac{Energy}{Pulse\,duration}$$

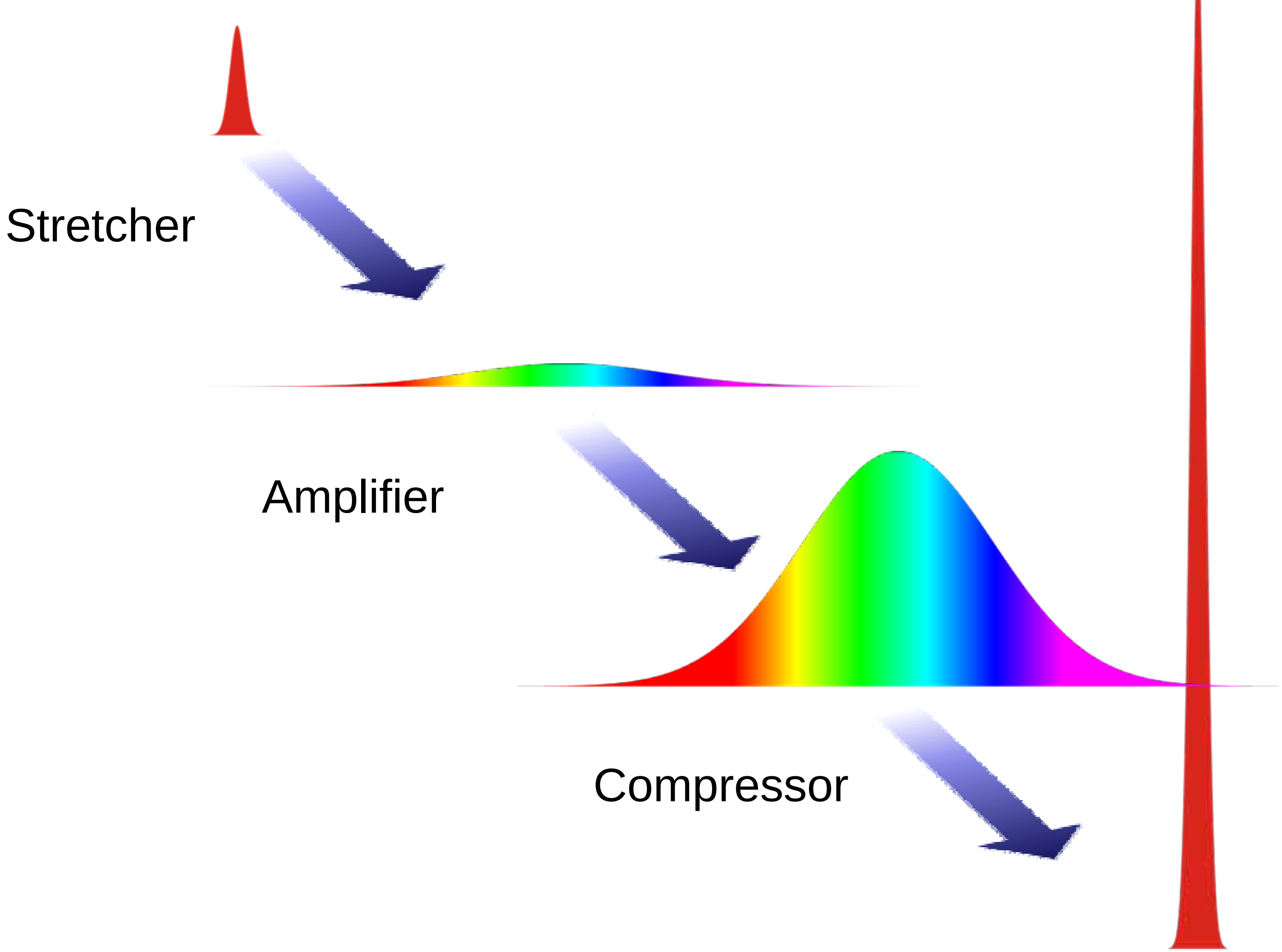
$$Intensity = \frac{Energy}{Pulse\,duration \cdot Area}$$

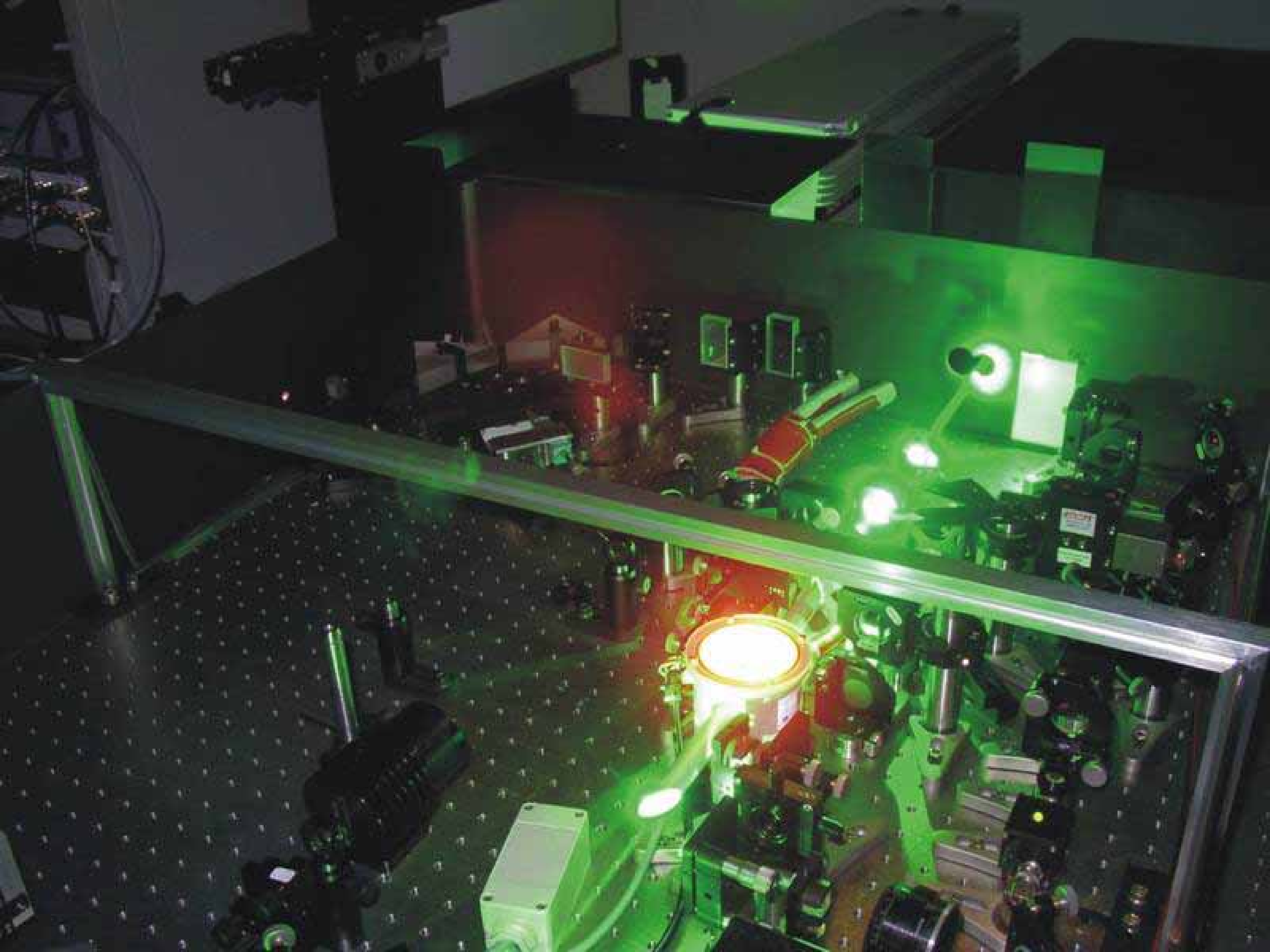
BIG lasers $Area \uparrow \Rightarrow Intensity \downarrow$



Chirped Pulse Amplification (CPA) $Pulse\,duration \uparrow \Rightarrow Intensity \downarrow$

Chirped pulse amplification (CPA)

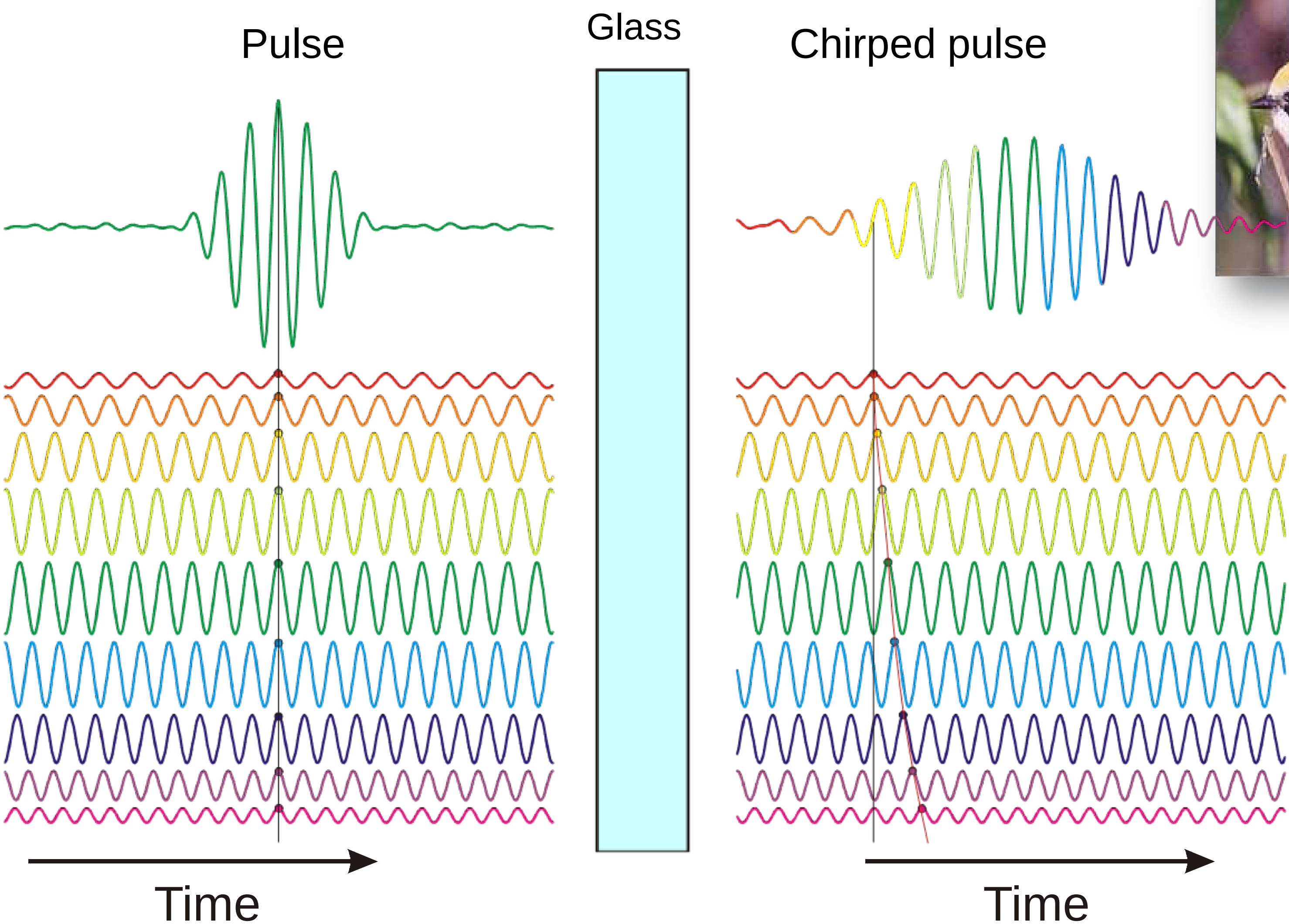




Parameters of our laser system

- Pulse duration: 25 fs
- Repetition rate: 1 kHz
- Spectral width: 750 nm – 840 nm
- Energy per pulse: 1 mJ (can heat 1 g H_2O by 1/4000 ^{0}C)
- Number of photons per pulse: 10^{15}
- Peak power: 40 GW (nuclear power plant typical 1-2 GW)
- Intensity in 10 µm focus: 50 PW/cm^2 (Solar constant 0.14 W/cm^2)
- Tunability with nonlinear optics: 200 nm – 2300 nm
- Pulse shaping in phase, amplitude and polarization

Dispersion of broadband light



Pulse shaping: mathematical description

Input pulse → Transfer function → Output pulse

$E_{\text{in}}(t)$ $\xrightarrow{\mathcal{F}}$ $\tilde{E}_{\text{in}}(\omega)$ → $\tilde{M}(\omega)$ → $\tilde{E}_{\text{out}}(\omega)$ $\xrightarrow{\mathcal{F}^{-1}}$ $E_{\text{out}}(t)$

$\mathcal{F}$ $$\tilde{E}(\omega) := \int_{-\infty}^{\infty} E(t)\, e^{-i\omega t}\, dt$$

Time domain

$E(t)$

Frequency domain

$\tilde{E}(\omega)$

$\mathcal{F}^{-1}$ $$E(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{E}(\omega)\, e^{i\omega t} d\omega$$

Mathematical description

Time domain		Freuqency domain
$\mathcal{E}(t)$	○—●	$\tilde{\mathcal{E}}(\omega)$
$\otimes\mathcal{M}(t)$ ↓		↓ $\cdot\tilde{\mathcal{M}}(\omega)$
$\mathcal{E}_{mod}(t) = \mathcal{E}(t) \otimes \mathcal{M}(t)$	○—●	$\tilde{\mathcal{E}}_{mod}(\omega) = \tilde{\mathcal{E}}(\omega) \cdot \tilde{\mathcal{M}}(\omega)$
		$\tilde{\mathcal{E}}_{mod}(\omega) = \tilde{\mathcal{E}}(\omega) \cdot e^{-i\varphi(\omega)}$
		Phase modulation
$\mathcal{M}(t)$	○—●	$\tilde{\mathcal{M}}(\omega)$

Taylor expansion of the phase function

$$\varphi(\omega) = \sum_{n=0} \frac{1}{n!} \frac{\partial^n \varphi}{\partial \omega^n}\bigg|_0 \cdot \omega^n \qquad \phi_n = \frac{\partial^n \varphi}{\partial \omega^n}\bigg|_0$$

- Absolute phase ϕ_0
- Linear phase ϕ_1
- Quadratic phase ϕ_2 (GDD, chirp)
- Cubic phase ϕ_3 (TOD)

- Sinusoidal modulation

Absolute phase $\tilde{\mathcal{E}}(\omega) \cdot e^{-i\phi_0}$

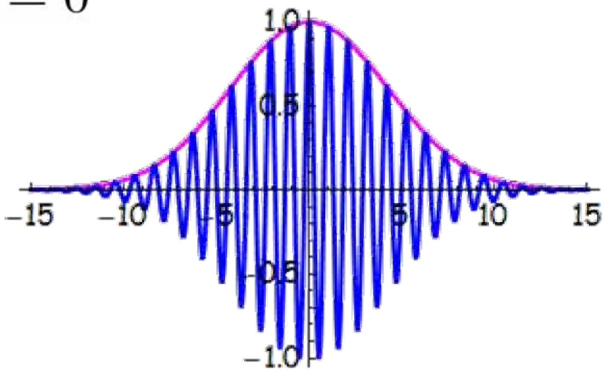
Is it physically relevant?

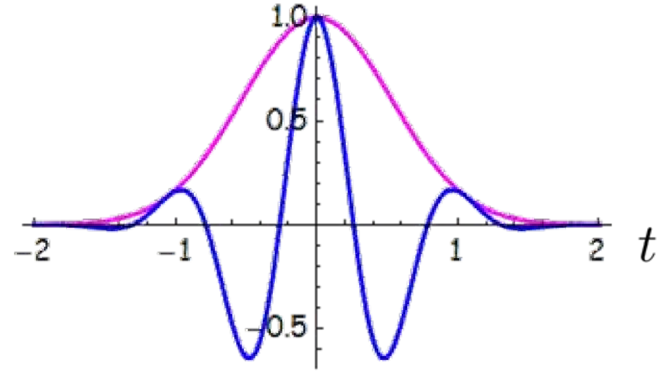
NO!

Yes!

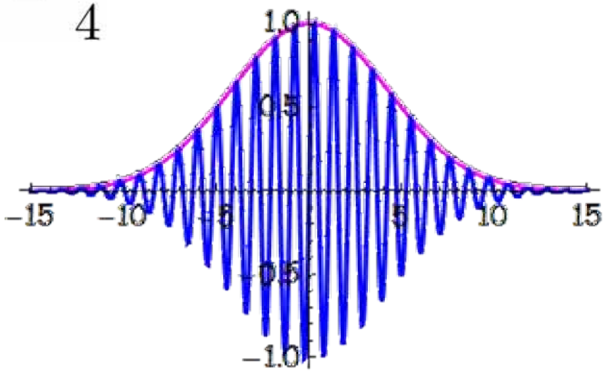
…indeed, for non-linear processes

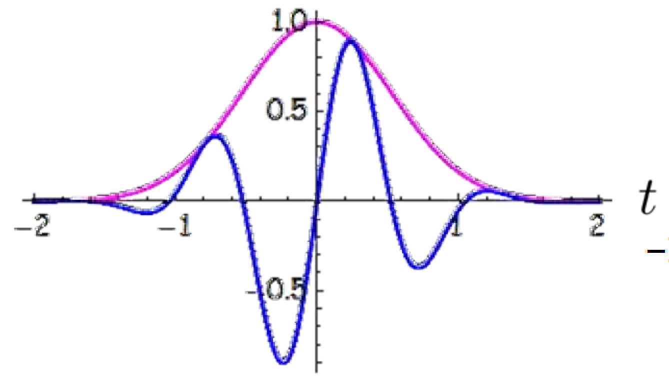
$\phi_0 = 0$

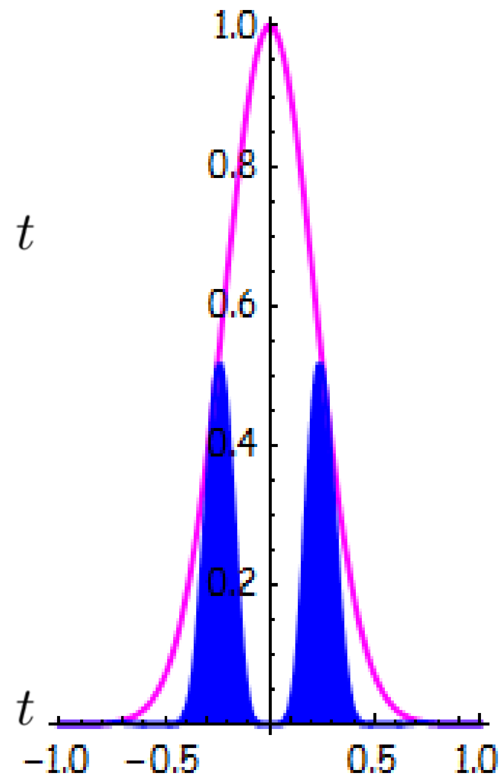




$\phi_0 = \frac{\pi}{4}$

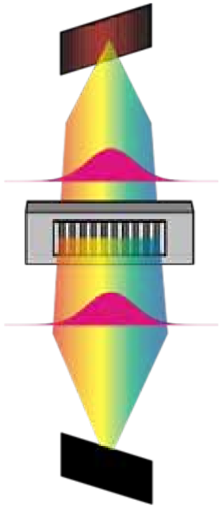


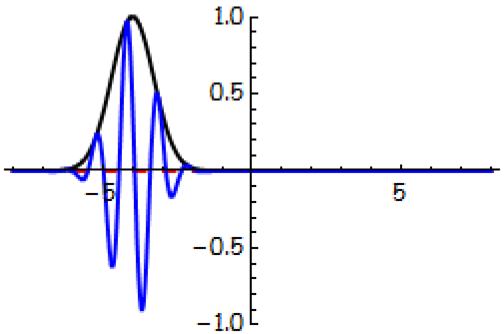




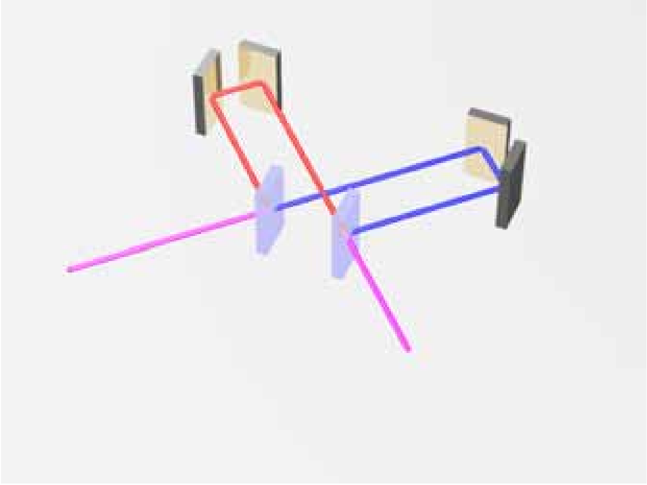
Linear phase $\tilde{\mathcal{E}}(\omega)\cdot e^{-i\phi_1\cdot\omega}$

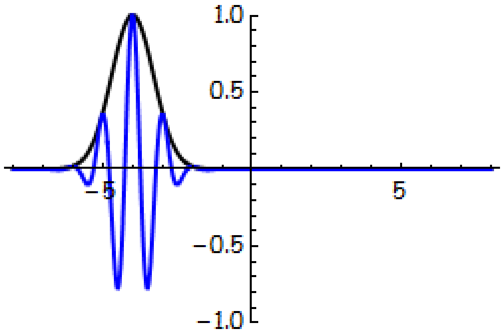
Phasenmodulation





Interferometer





Quadratic spectral phase $\tilde{\mathcal{E}}(\omega)\cdot e^{-i\frac{\phi_2}{2}\cdot\omega^2}$

$$\mathcal{E}(t)=\frac{\mathcal{E}_0}{2}e^{-2\ln(2)\left(\frac{t}{\Delta t}\right)^2}$$

FWHM = Δt

$$\otimes\frac{e^{\frac{it^2}{2\phi_2}}}{\sqrt{2\pi i\,\phi_2}}$$

$$\mathcal{E}_{mod}(t)$$

$$=\frac{\mathcal{E}_0\Delta t}{2}\frac{e^{-\frac{2t^2\ln(2)}{\Delta t^2+4i\phi_2\ln(2)}}}{\sqrt{\Delta t^2+4i\phi_2\ln(2)}}$$

$$\tilde{\mathcal{E}}(\omega)=\frac{\mathcal{E}_0\Delta t}{2}\sqrt{\frac{\pi}{2\ln(2)}}e^{-\frac{(\omega\Delta t)^2}{8\ln(2)}}$$

$$\cdot e^{-i\frac{\phi_2}{2!}\cdot\omega^2}$$

$$\tilde{\mathcal{E}}_{mod}(\omega)=\tilde{\mathcal{E}}(\omega)\cdot e^{-i\frac{\phi_2}{2!}\cdot\omega^2}$$

Quadratic spectral phase: chirp

ϕ_2 [fs²]

$$\mathcal{E}_{mod}(t) = \frac{\mathcal{E}_0 \Delta t}{2} \frac{e^{-\frac{2t^2 \ln(2)}{\Delta t^2 + 4i\phi_2 \ln(2)}}}{\sqrt{\Delta t^2 + 4i\phi_2 \ln(2)}} \Rightarrow$$

$$\beta = \frac{\Delta t^2}{8 \ln(2)} \quad [\text{fs}^2]$$

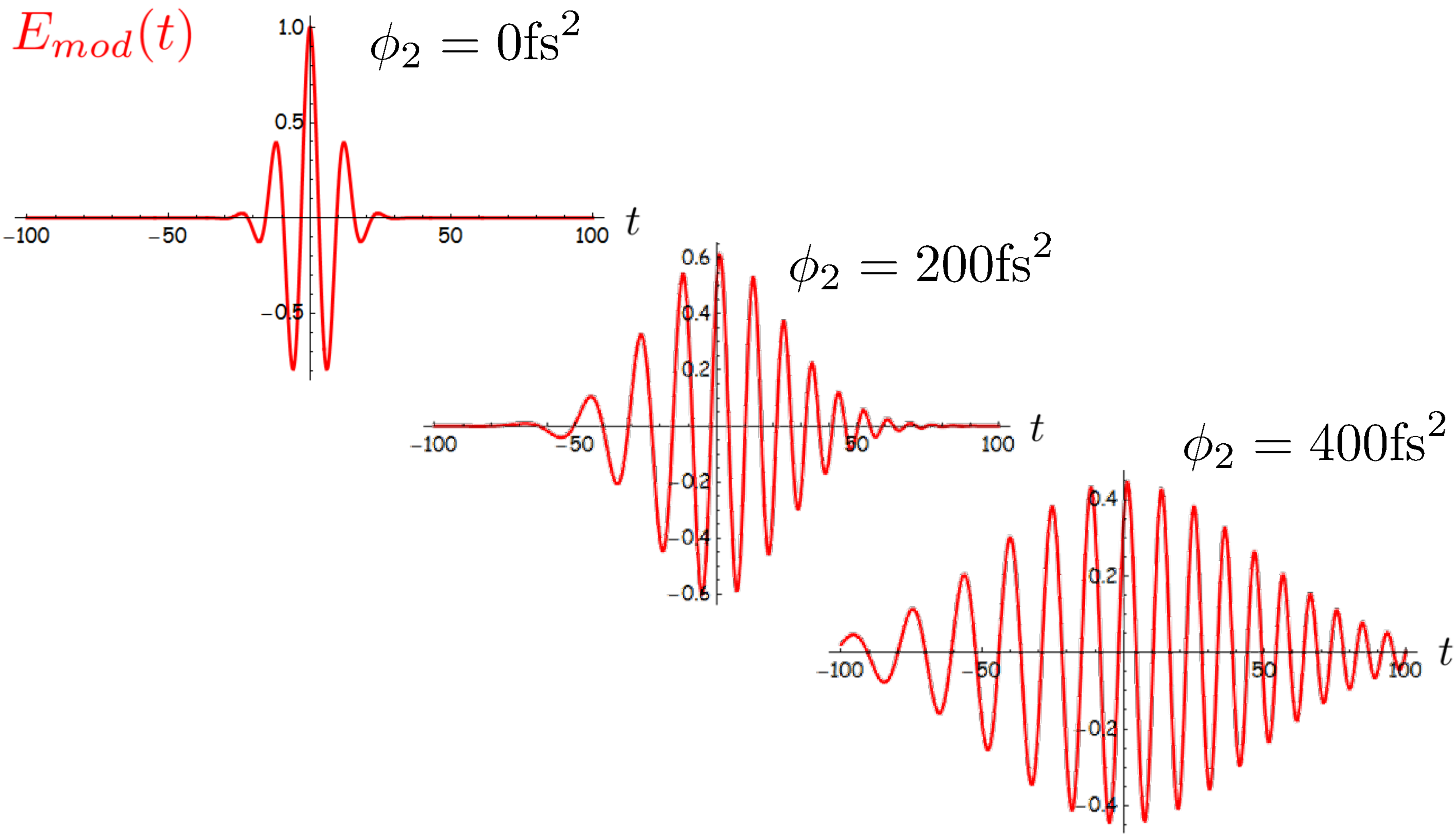
$$\boxed{\mathcal{E}_{mod}(t) = \frac{\mathcal{E}_0}{2\gamma^{\frac{1}{4}}} e^{-\frac{t^2}{4\beta\gamma}} e^{i(\alpha t^2 - \varepsilon)}}$$

$$\gamma = 1 + \frac{\phi_2^2}{4\beta^2}$$

$$\alpha = \frac{\phi_2}{8\beta^2\gamma} = \left\{ 2\phi_2 + \frac{\Delta t^4}{8\,\phi_2 [\ln(2)]^2} \right\}^{-1} \quad [\text{fs}^{-2}]$$

$$\varepsilon = \arctan\left[\frac{\phi_2}{2\beta}\right]$$

Controlling the chirp by ϕ_2



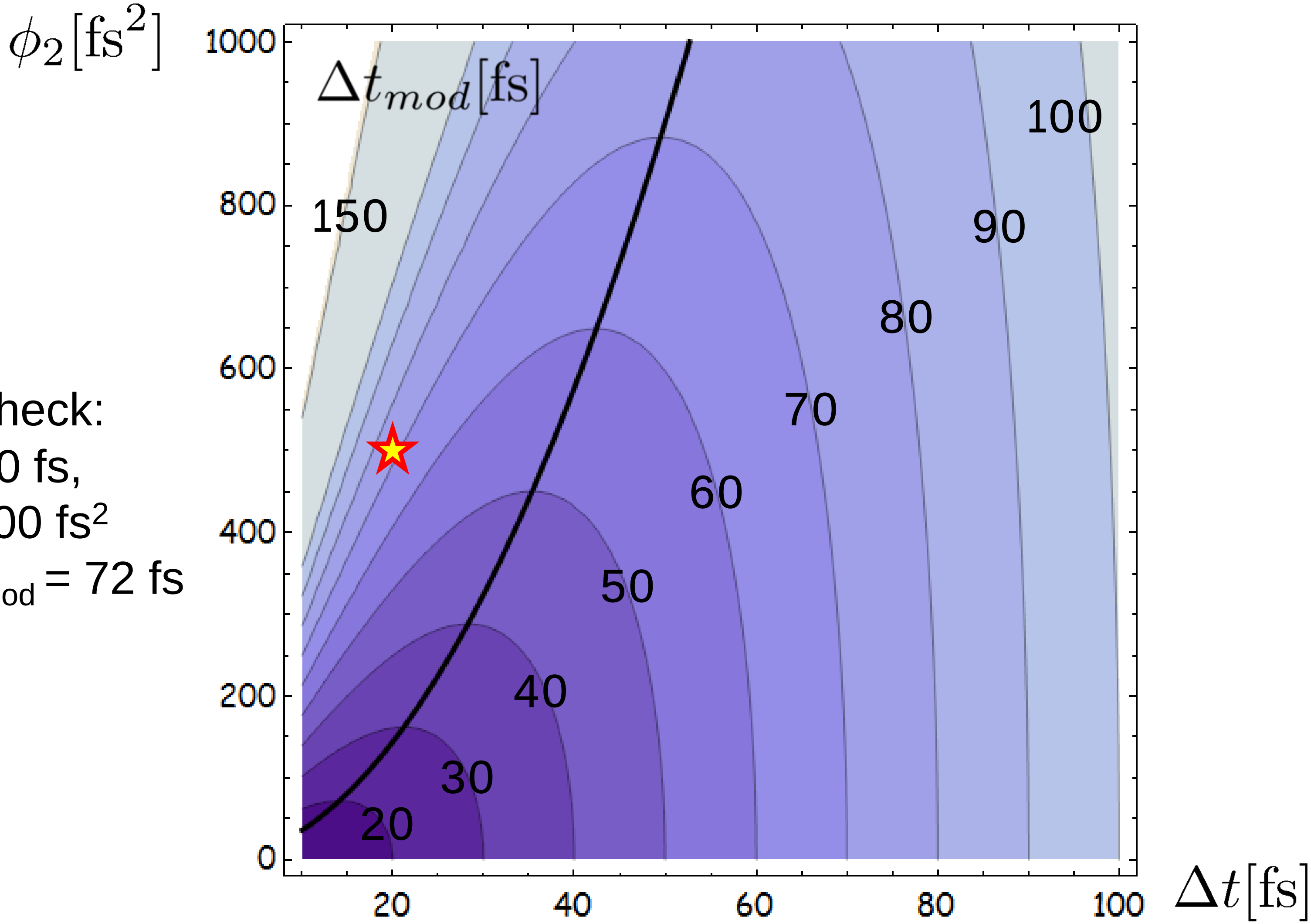
Duration of a chirped pulse

$$\mathcal{E}_{mod}(t) = \frac{\mathcal{E}_0}{2\gamma^{\frac{1}{4}}} e^{-\frac{t^2}{4\beta\gamma}} e^{i(\alpha t^2 - \varepsilon)}$$

$$\Delta t_{mod} = \sqrt{\Delta t^2 + [\ln(16)]^2 \left(\frac{\phi_2}{\Delta t}\right)^2}$$

Δt \ ϕ_2	100 fs^2	200 fs^2	500 fs^2	1000 fs^2	2000 fs^2	5000 fs^2
10 fs	29.5	56.3	139	277.4	554.6	1386.3
20 fs	24.3	34.2	72.1	140.1	278	693.4
30 fs	31.4	35.2	55.1	97.2	187.3	463.1
100 fs	100	100.2	101	103.8	114.3	170.9

Duration of a chirped pulse

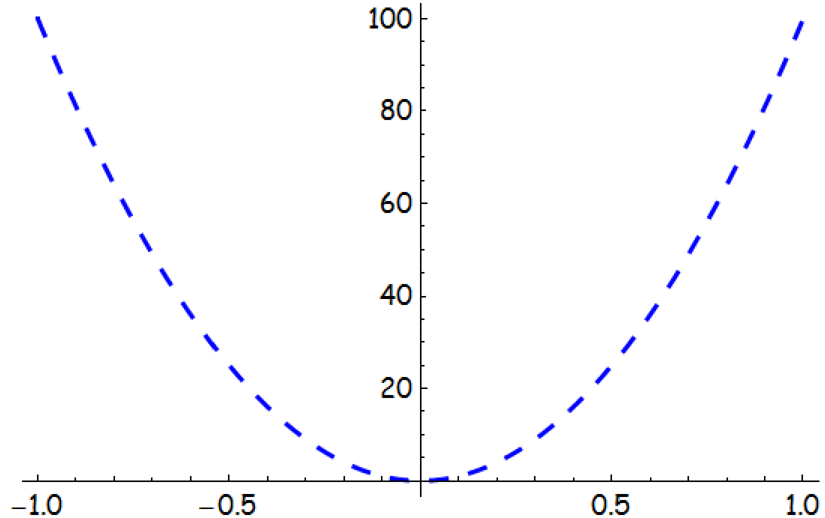


Check:
Δt = 20 fs,
ϕ_2 = 500 fs^2
$\Rightarrow \Delta t_{mod}$ = 72 fs

Spectral physical picture: group delay

$$\varphi(\omega) = \frac{\phi_2}{2!} \cdot \omega^2$$

Spectral phase

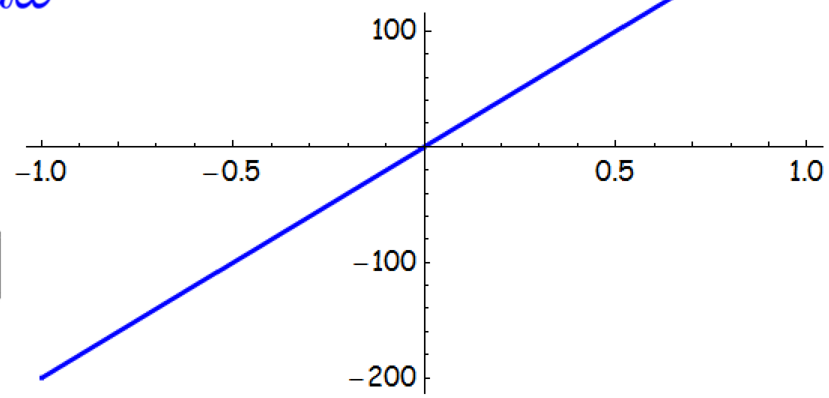


ω

$$\phi_2 = 200\mathrm{fs}^2$$

$$T_g(\omega) = GD(\omega) = \frac{d}{d\omega}\varphi(\omega) = \phi_2 \cdot \omega$$

Group delay



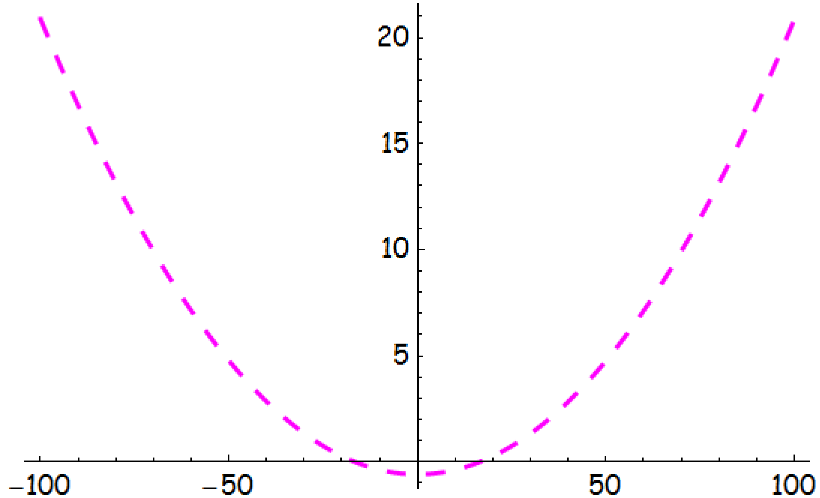
ω

$$T_g(\omega) = GD(\omega)\ [\mathrm{fs}]$$

Temporal physical picture: instantaneous frequency

$$\zeta(t) = \alpha \cdot t^2 - \varepsilon$$

Temporal phase

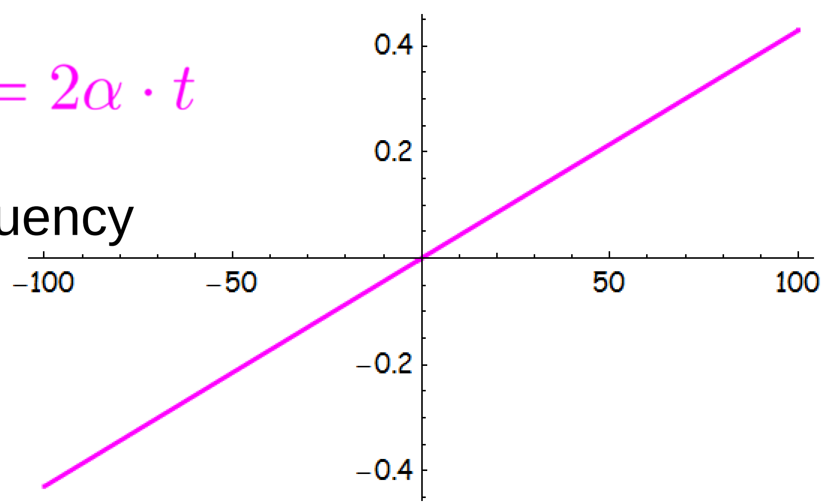


$$\alpha = 2.14\,10^{-3}\,\mathrm{fs}^{-2}$$

$$\varepsilon = 0.59\,\mathrm{rad}$$

$$\Delta\omega(t) = \frac{d}{dt}\zeta(t) = 2\alpha \cdot t$$

Instantaneous frequency



$\Delta\omega(t)\ [\mathrm{fs}^{-1}]$

Summary chirp

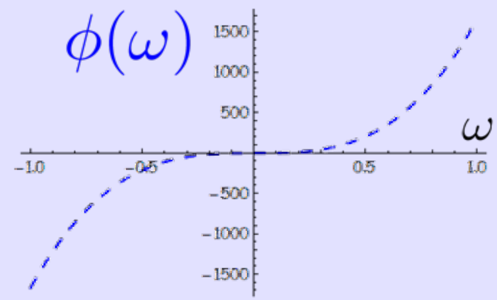
- The linear chirp is generated by a quadratic spectral phase function $\varphi(\omega)$
- …corresponding to a linear $T_g(\omega)$ (Group Delay Dispersion, GDD).
- A Gaussian envelope pulse is stretched symmetrically and stays Gaussian reducing the intensity
- Short pulses will be stretched more than long pulses (for a given ϕ_2) .
- The sign of ϕ_2 controls the „direction“ of the chirp: > 0 up-chirp, < 0 down-chirp
- The temporal envelope is complex valued characterized by a quadratic temporal phase $\zeta(t)$
- …leading to a linear increase / decrease of the instantaneous frequency $\Delta\omega(t)$
- There is a maximum (temporal) chirp rate α for a given pulse duration

Cubic spectral phase (TOD) $\tilde{\mathcal{E}}(\omega)\cdot e^{-i\frac{\phi_3}{3!}\cdot\omega^3}$

$\mathcal{E}(t)$ ○——● $\tilde{\mathcal{E}}(\omega)$

$\otimes\,\Omega Ai\left[-\sigma(\phi_3)\,\Omega\, t\right]$ ↓

↓ $\cdot e^{-i\frac{\phi_3}{3!}\cdot\omega^3}$



$$\mathcal{E}_{mod}(t) = \mathcal{E}(t)\otimes\,\Omega Ai\left[-\sigma(\phi_3)\,\Omega t\right]$$

○——●

$$\tilde{\mathcal{E}}_{mod}(\omega) = \tilde{\mathcal{E}}(\omega)\, e^{-i\frac{\phi_3}{3!}\cdot\omega^3}$$

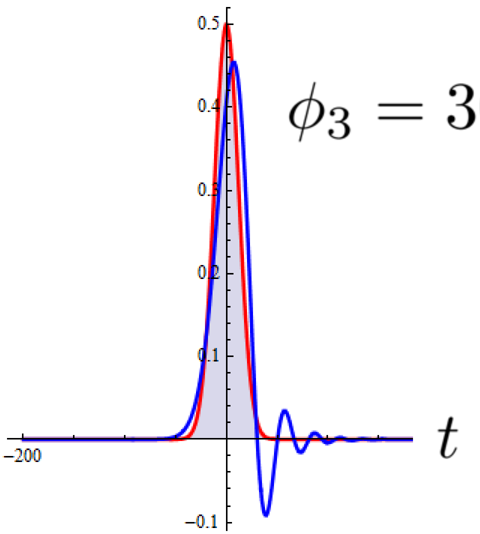
$$\Omega = \sqrt[3]{\frac{2}{|\phi_3|}}$$

ϕ_3 [rad fs^3]

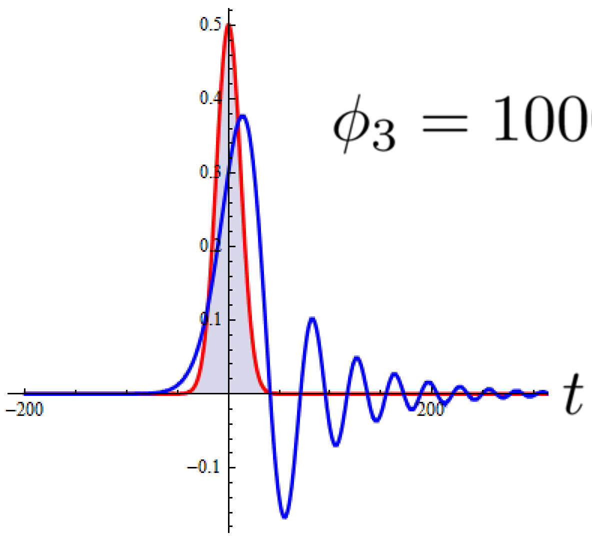
TOD: ϕ_3 variation

$$\Delta t = 20[\mathrm{fs}]$$

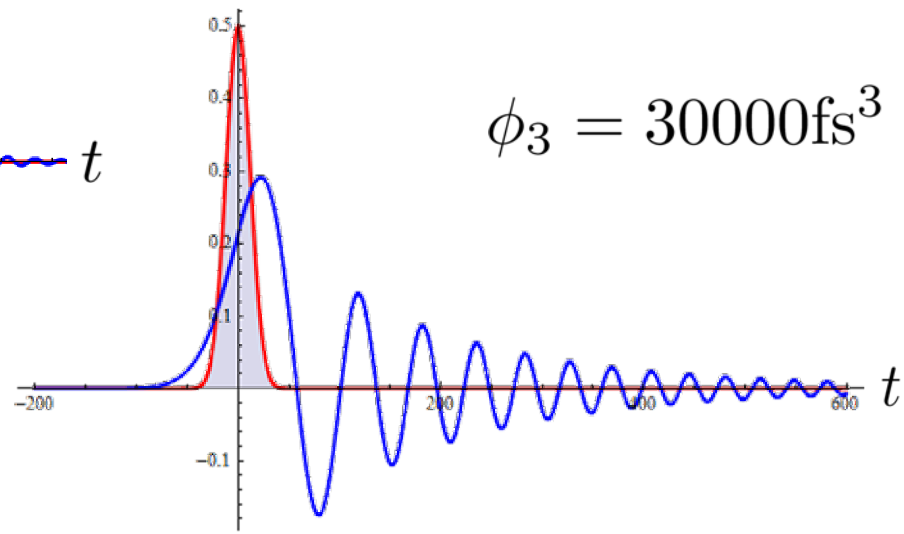
$$\mathcal{E}_{mod}(t) = f \cdot \frac{\mathcal{E}_0 \Delta t}{2\phi} e^{\frac{\ln(2)}{2} \frac{\frac{2}{3}\tau - t}{\tau 12}} Ai\left[\frac{\tau - t}{\Delta t}\right]$$



$$\phi_3 = 3000\mathrm{fs}^3$$

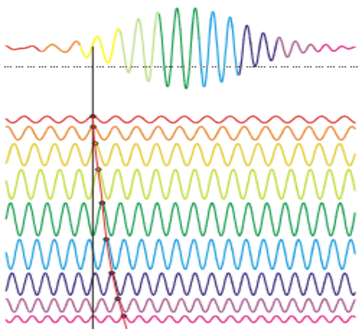


$$\phi_3 = 10000\mathrm{fs}^3$$

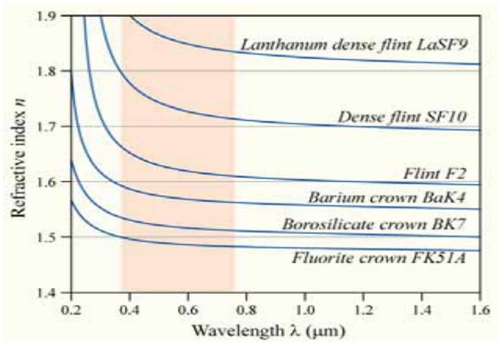


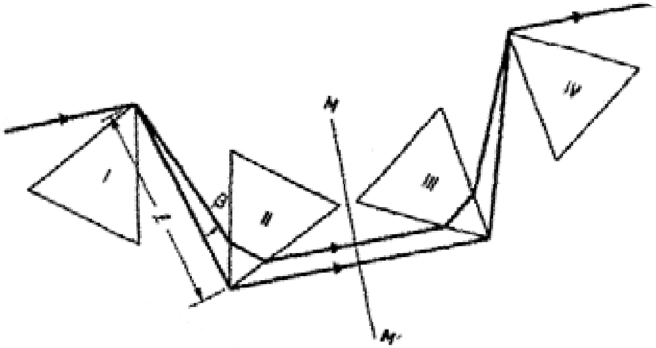
$$\phi_3 = 30000\mathrm{fs}^3$$

Counteracting dispersion in an optical system



In (most) transparent media red frequency components travel faster than blue ones leading to up-chirped pulses





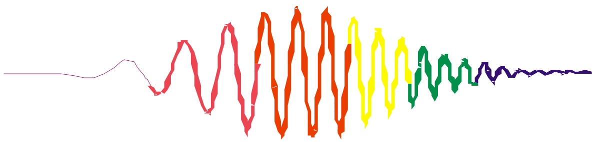
Find optical system where blue components travel faster (shorter optical length) than red ones introducing negative dispersion

Several realizations:

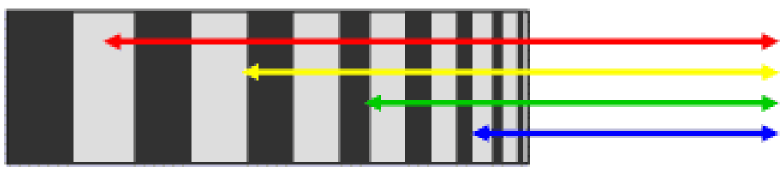
- chirped mirrors
- angular dispersion (grating and prism arrangements)
- programmable pulse shapers

Fork et. al., Opt. Lett, **9**, *150*, (1984)

Chirped mirrors

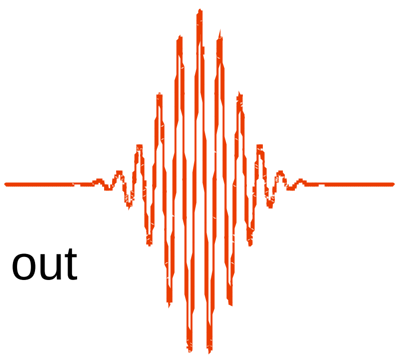


up chirped in

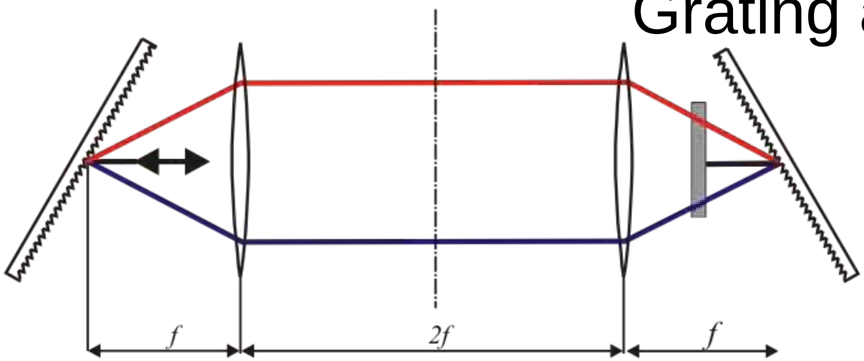


Long wavelengths penetrate deeper into mirror and experience larger group delay (anomalous chromatic dispersion)

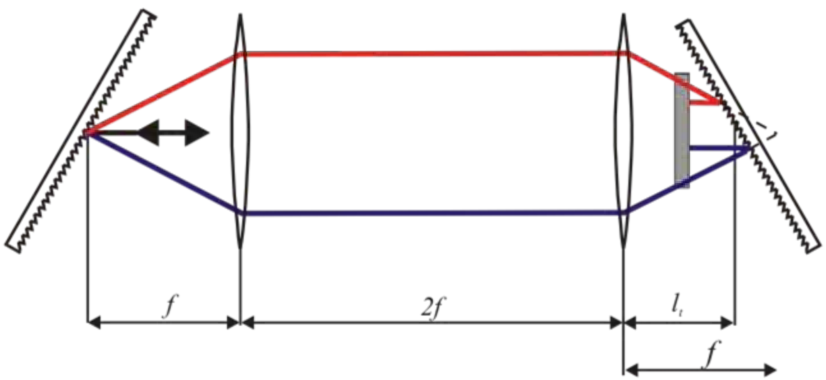
compressed out



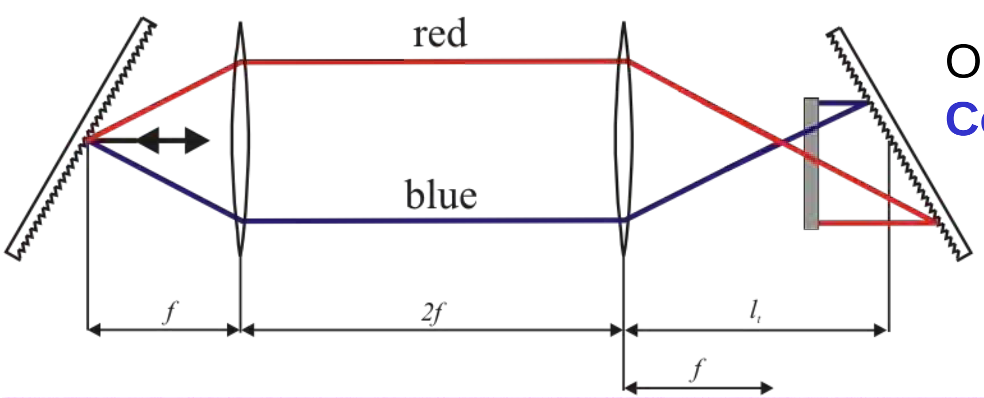
Grating arrangements



Optical path “red” equals optical path “blue”
Zero Dispersion Compressor
often used in pulse shaping devices

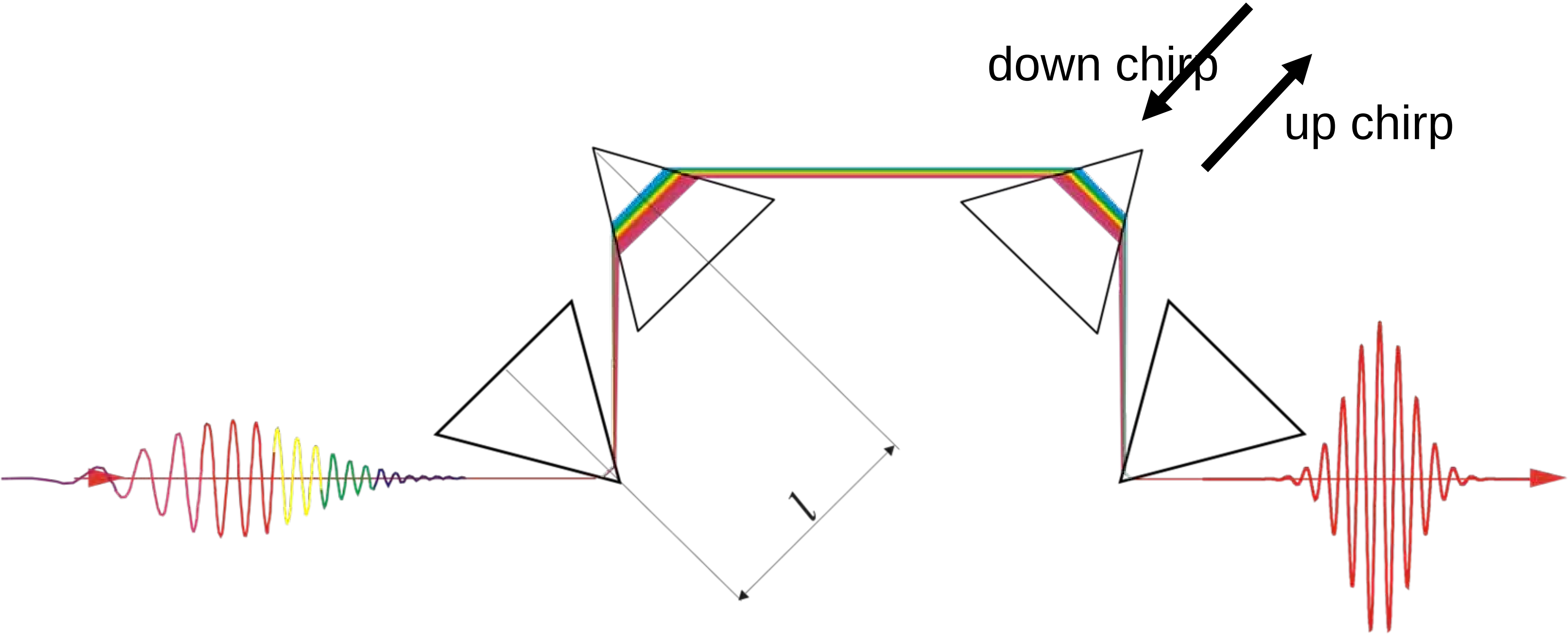


Optical path “red” smaller optical path “blue”
Stretcher



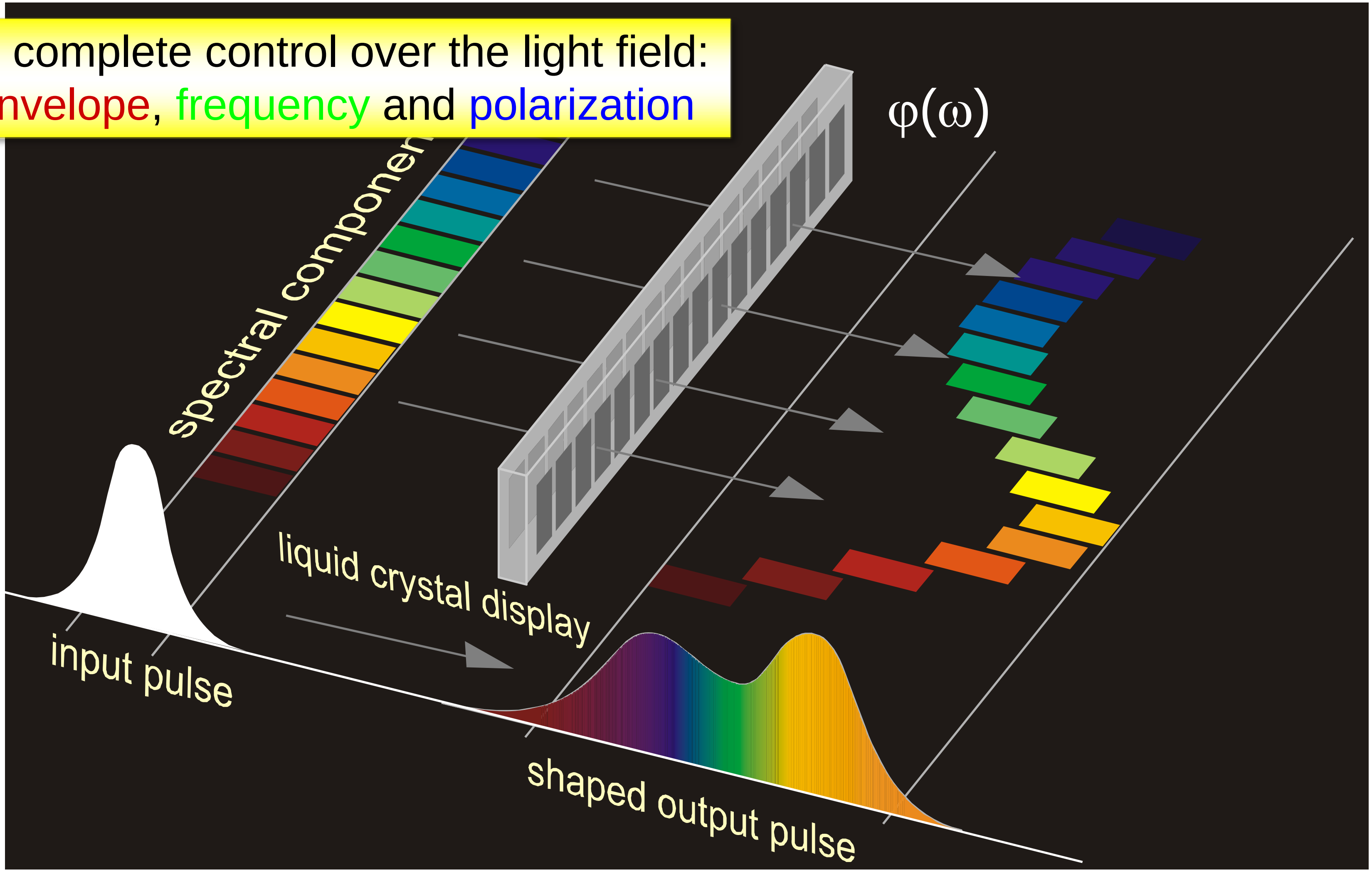
Optical path “red” larger optical path “blue”
Compressor

Prism compressors

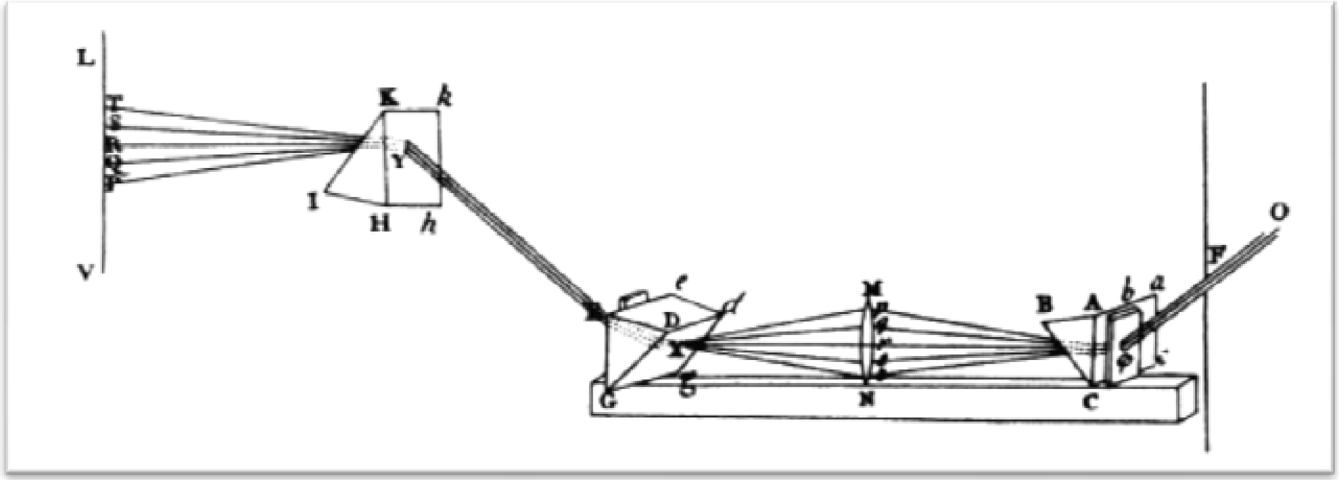


Shaping ultrashort light pulses by Fourier synthesis

⇒ complete control over the light field:
envelope, frequency and polarization

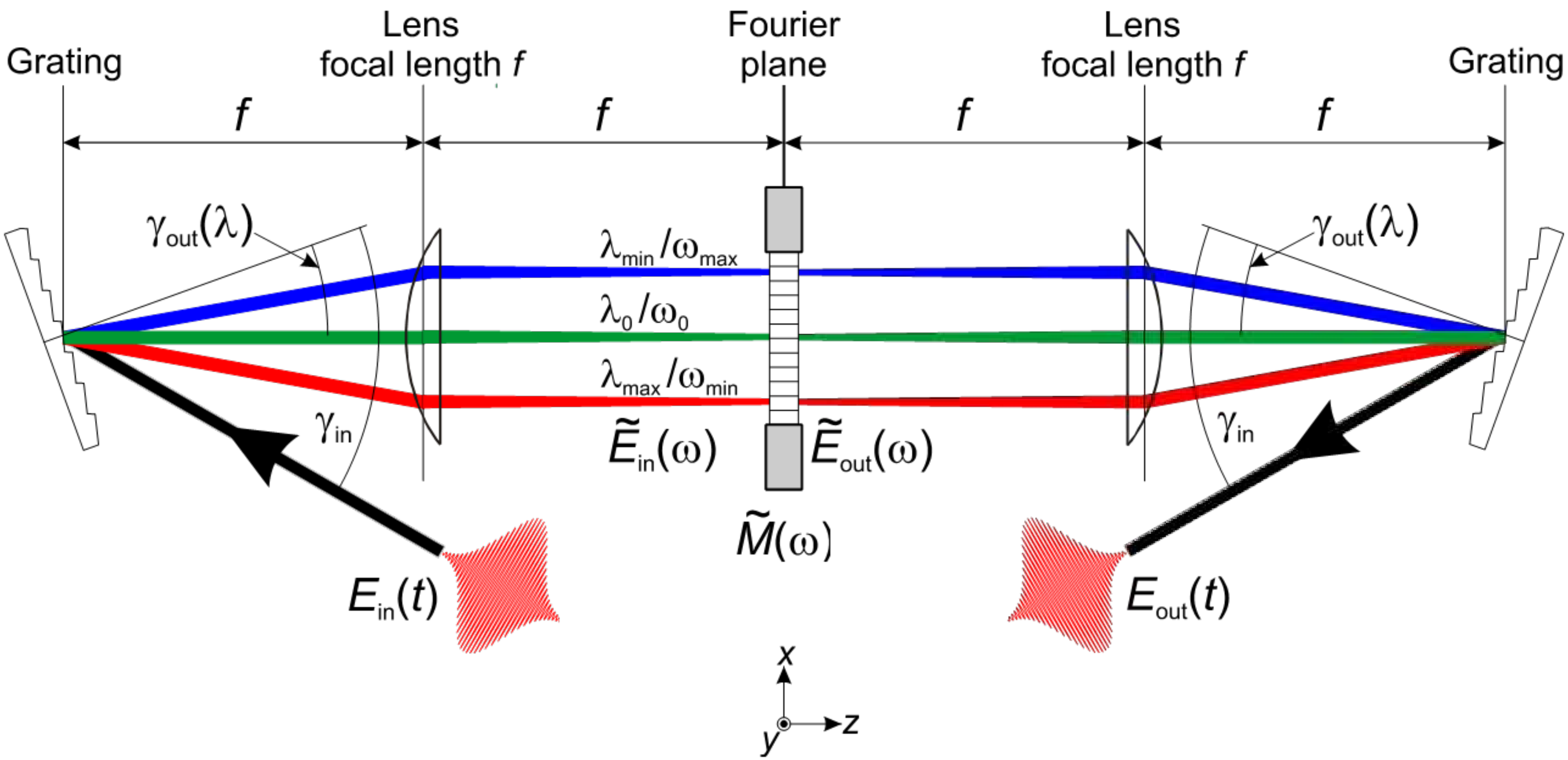


Shaping light: an early experimental layout



Sir Isaac Newton
Opticks *(1721 edn), book I, part II, fig.16.*

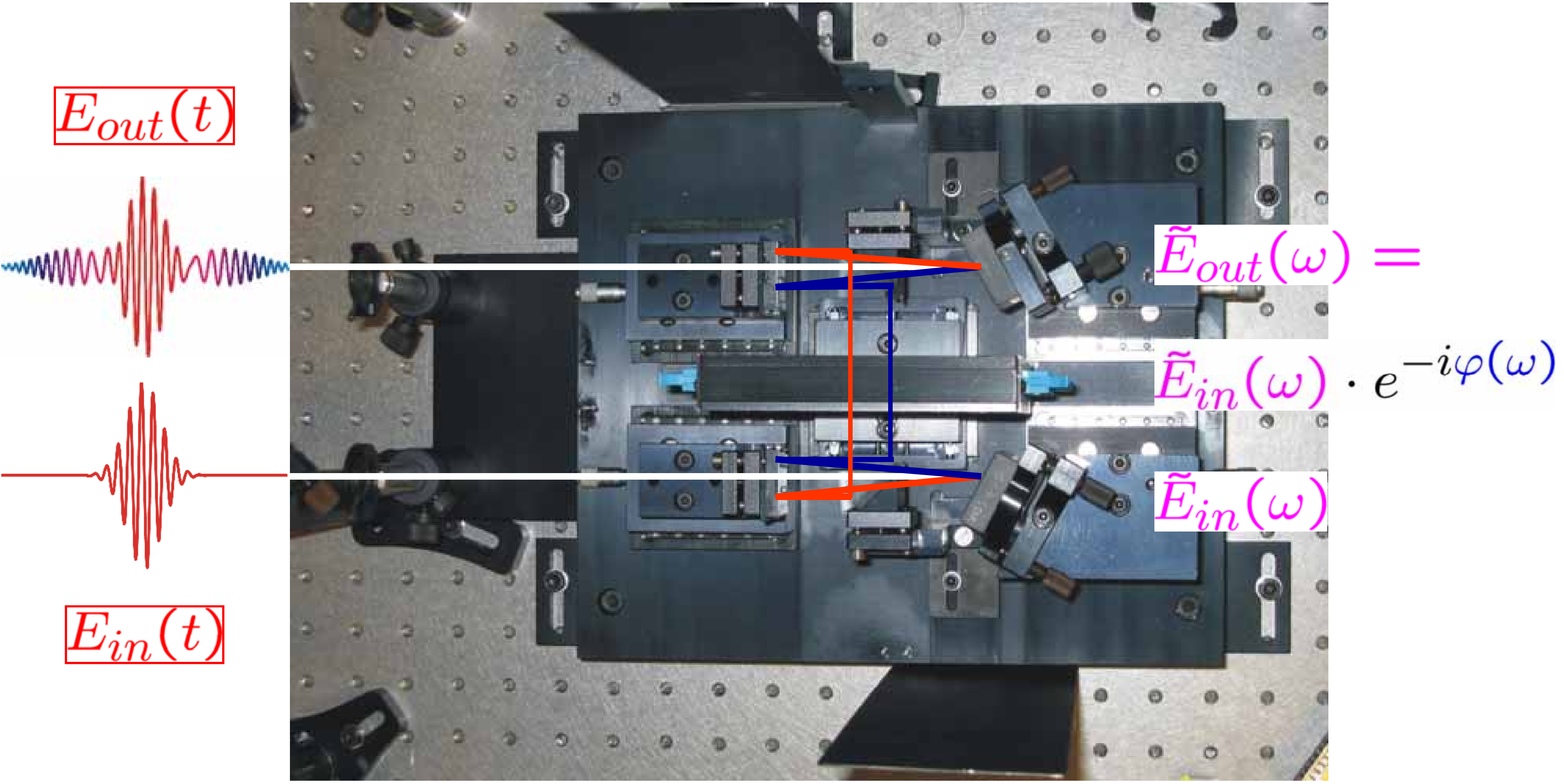
Fourier transform pulse shaper



$E_{in}(t)$ —FT→ $\tilde{E}_{in}(\omega)$ → $\tilde{M}(\omega)$ → $\tilde{E}_{out}(\omega)$ —FT^{-1}→ $E_{out}(t)$

Martínez: IEEE J. Quantum Electron 24(12), 2530-2536 (1988), Weiner et al.: JOSA B 5(8), 1563-1572 (1988)

Compact pulse shaper



Example: sinusoidal phase modulation $\tilde{\mathcal{E}}(\omega) \cdot e^{-iA\sin(\omega \cdot T + \phi)}$

$$\mathcal{E}(t) \quad \circ\!\!-\!\!\bullet \quad \tilde{\mathcal{E}}(\omega)$$

$$\otimes \sum_n J_n(A) e^{-in\phi}\, \delta(t - nT) \qquad \cdot e^{-iA\sin(\omega \cdot T + \phi)}$$

$$\mathcal{E}_{mod}(t) = \sum_n J_n(A) e^{-in\phi}\, \mathcal{E}(t - nT) \quad \circ\!\!-\!\!\bullet \quad \tilde{\mathcal{E}}_{mod}(\omega) = \tilde{\mathcal{E}}(\omega) \cdot e^{-iA\sin(\omega \cdot T + \phi)}$$

A [rad] T [fs] ϕ [rad]

Sinusoidal phase modulation $\tilde{\mathcal{E}}(\omega) \cdot e^{-iA\sin(\omega \cdot T + \phi)}$

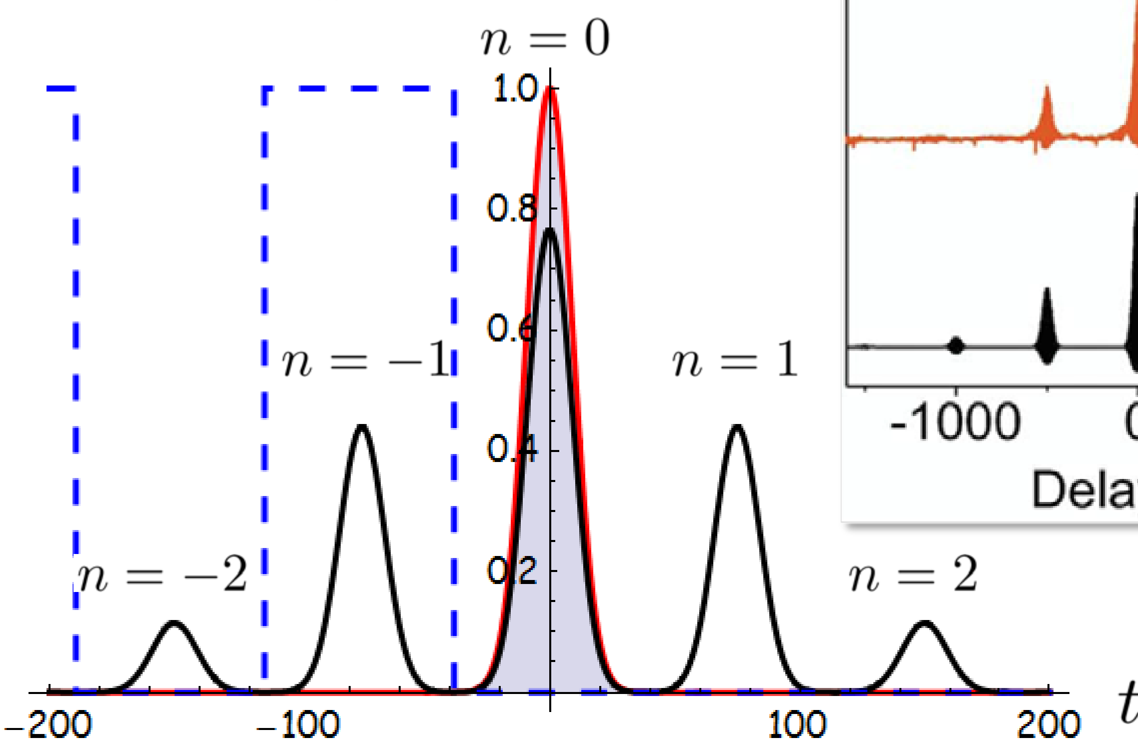
$$\mathcal{E}_{mod}(t) = \sum_n J_n(A) e^{-in\phi}\, \mathcal{E}(t - nT)$$

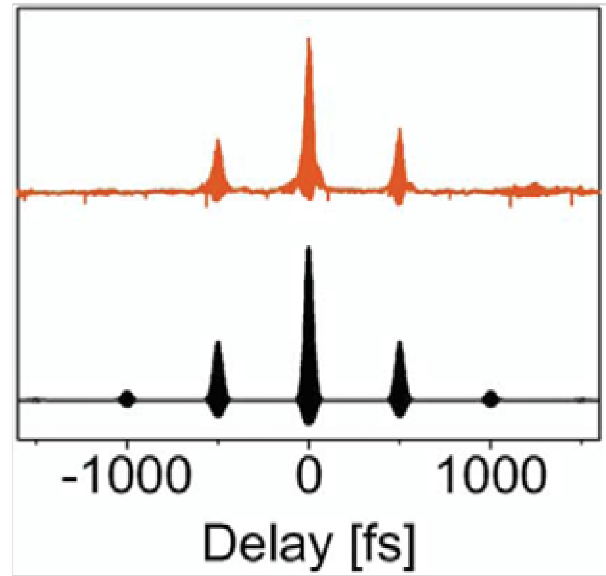
$A = 1.0$

$T = 75\text{fs}$

$\phi = 0$

$\Delta t = 15\text{fs}$

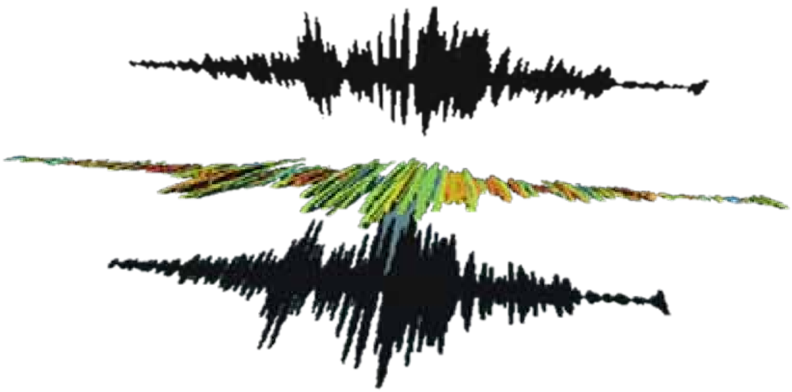




Sinusoidal phase modulation produces pulse trains

New twist in pulse shaping: polarization shaping

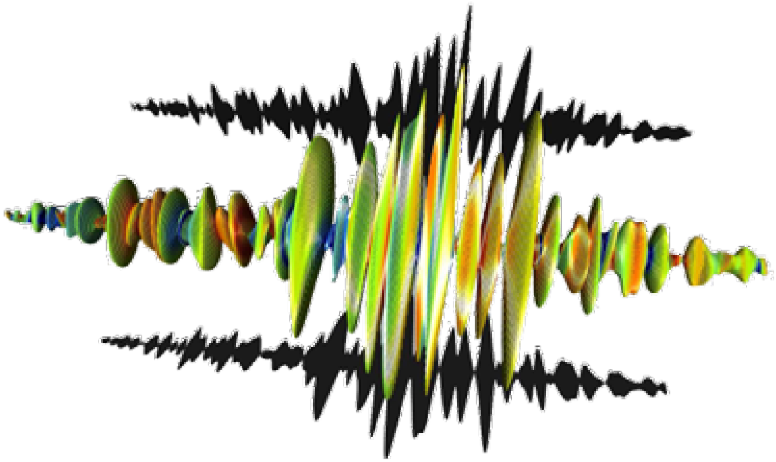
Scalar



- Modulation of intensity and phase
- Linearly polarized of E-field

Review:
Weiner: Rev. Sci. Instrum. ***71****, 1929, (2000)*
Rev. Sci. Inst., ***74****, 4950, (2003)*

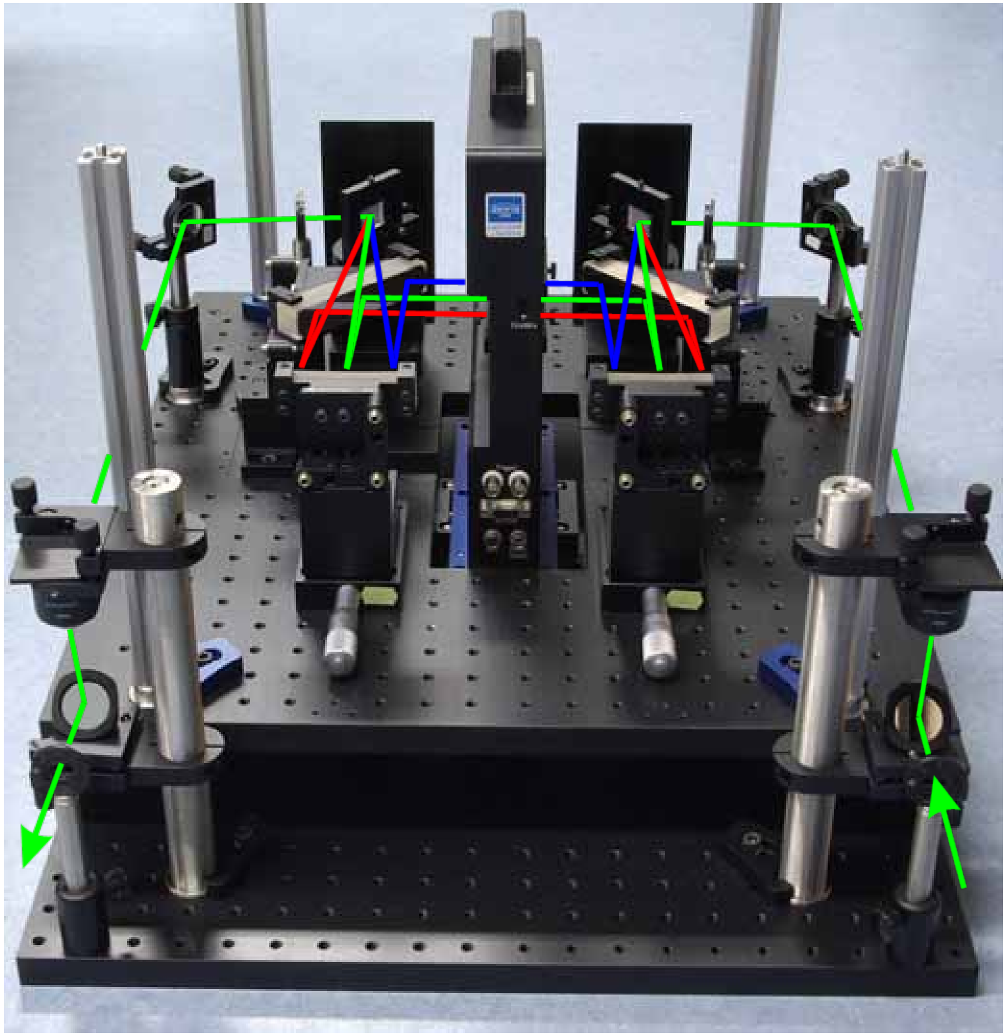
Vectorial



- Controlling intensity, phase and polarization
- Polarization state varies within a single pulse

Brixner et al.: Opt. Lett. ***26****, 557, (2001)*

A compact set-up for polarization shaping



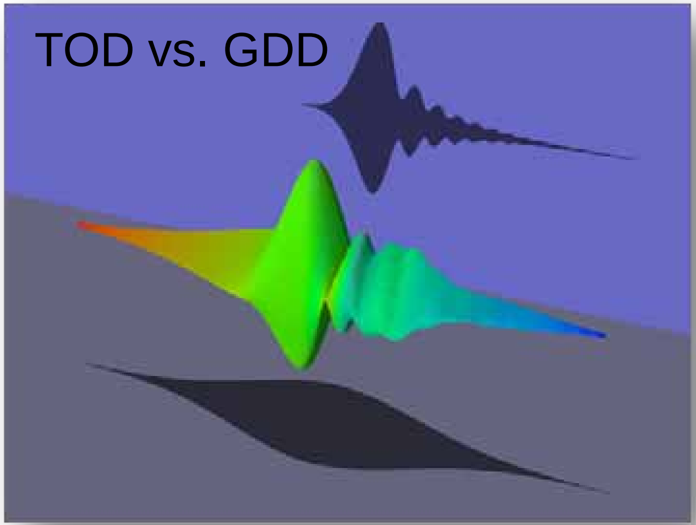
Key features:

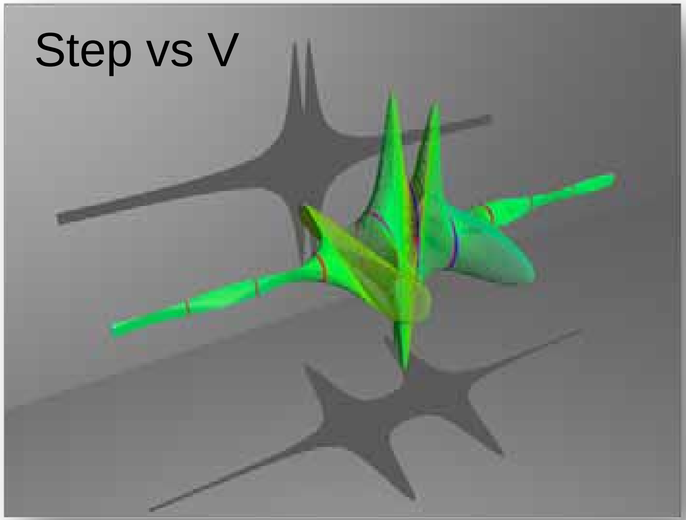
- Polarization shaping
- Phase & amplitude shaping
- 2x 640 pixel modulator

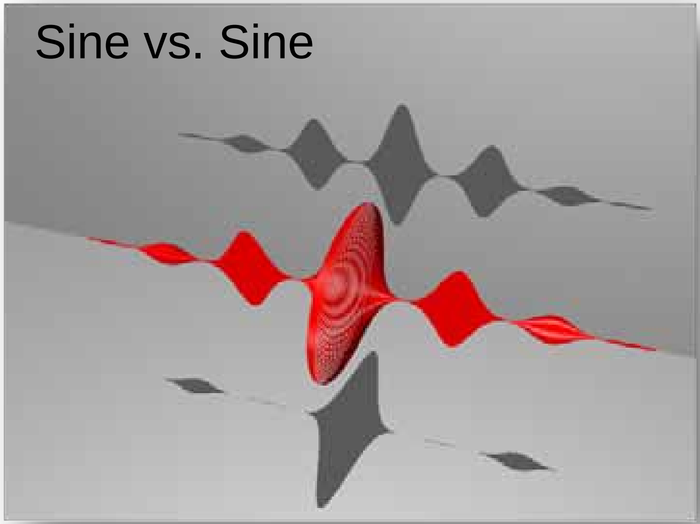
High spectral resolution
0.16 nm @ 800 nm

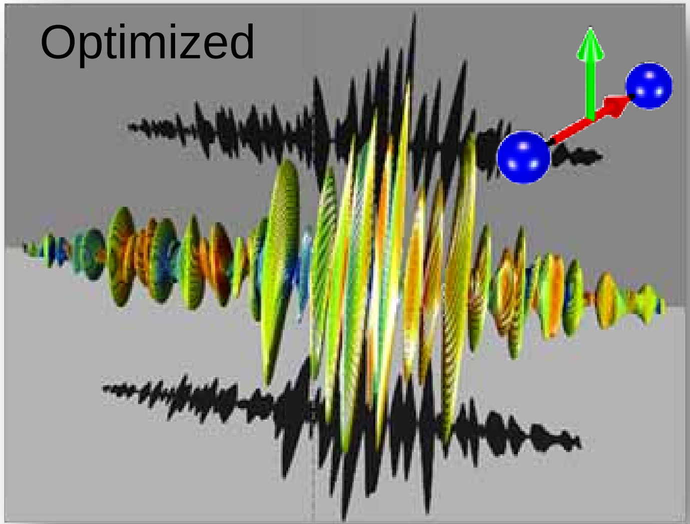
Large temporal window
> 10 ps

Pulse gallery





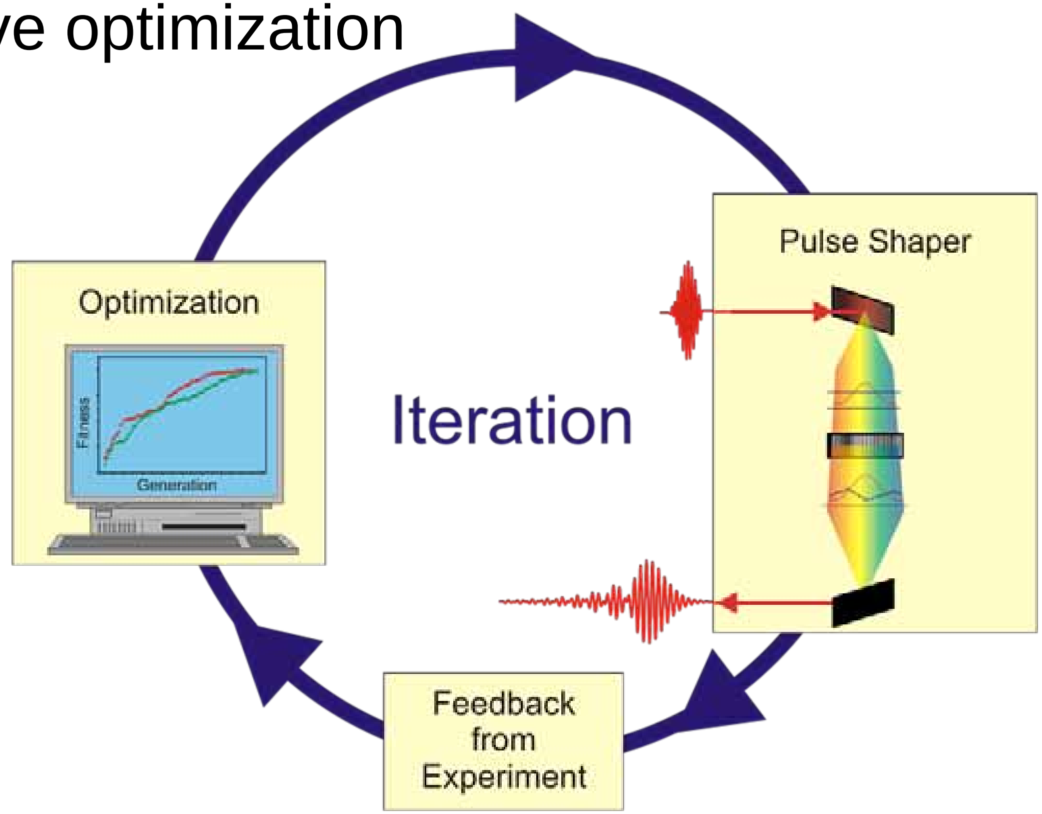


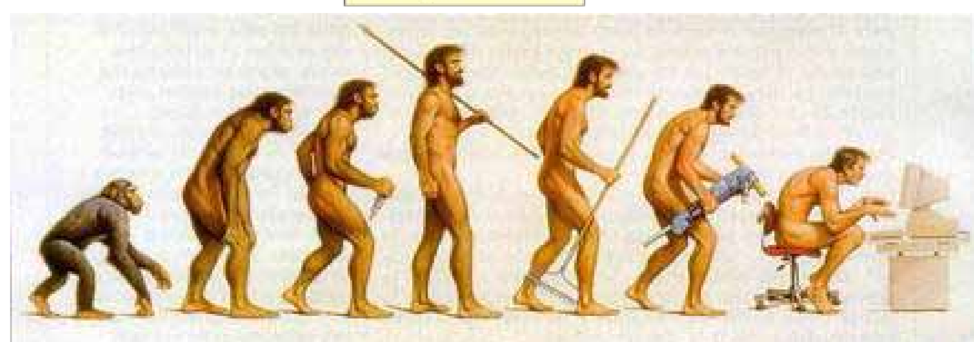


Phys. Rev. Lett, ***92***, *208301*, (2004)

Adaptive optimization

- Complex systems
- No *a priori* knowledge required
- Feedback by experiment
- Genetic optimization algorithm
- Iterative



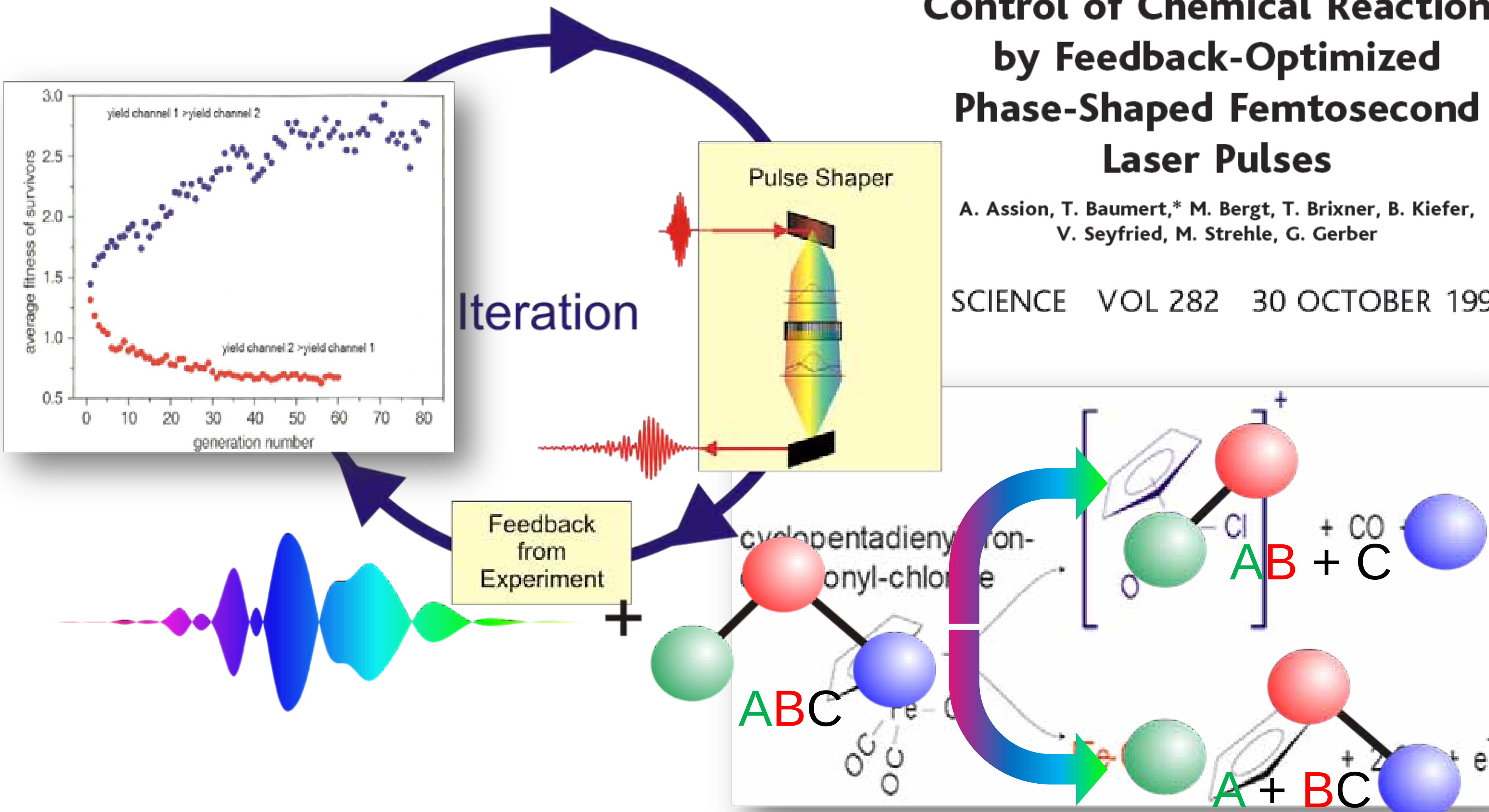


Laser control by adaptive optimization

Control of Chemical Reactions by Feedback-Optimized Phase-Shaped Femtosecond Laser Pulses

A. Assion, T. Baumert,* M. Bergt, T. Brixner, B. Kiefer, V. Seyfried, M. Strehle, G. Gerber

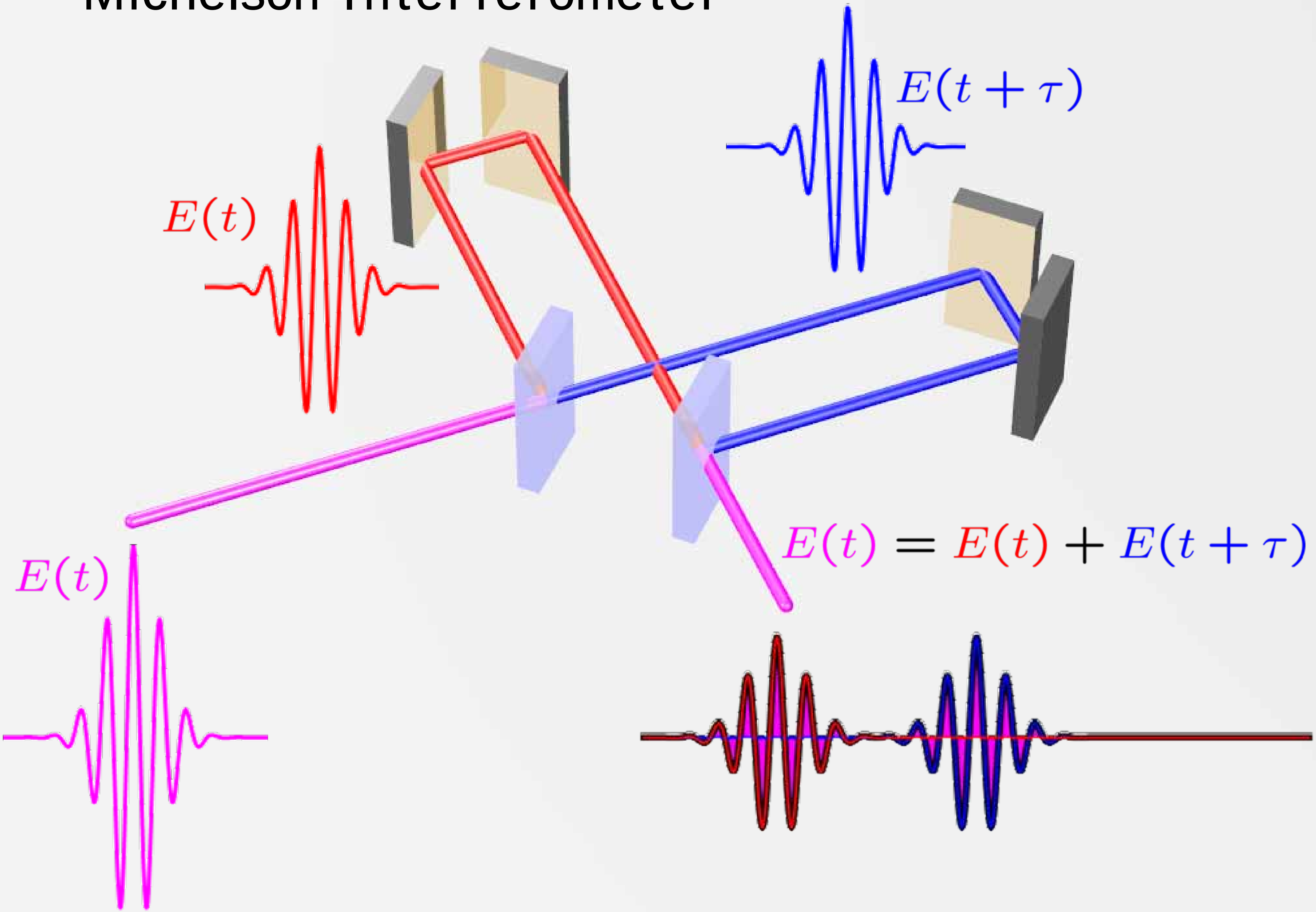
SCIENCE VOL 282 30 OCTOBER 1998



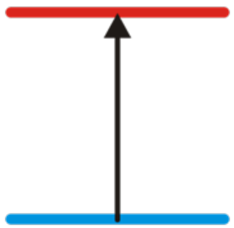
Pulse characterization

- Time domain
- Frequency domain
- Joint time frequency domain

Michelson Interferometer



Signals



One photon

$$S_{linear}(\tau) = \int_{-\infty}^{\infty} \{E(t) + E(t+\tau)\}^2 \, dt$$

Two photons

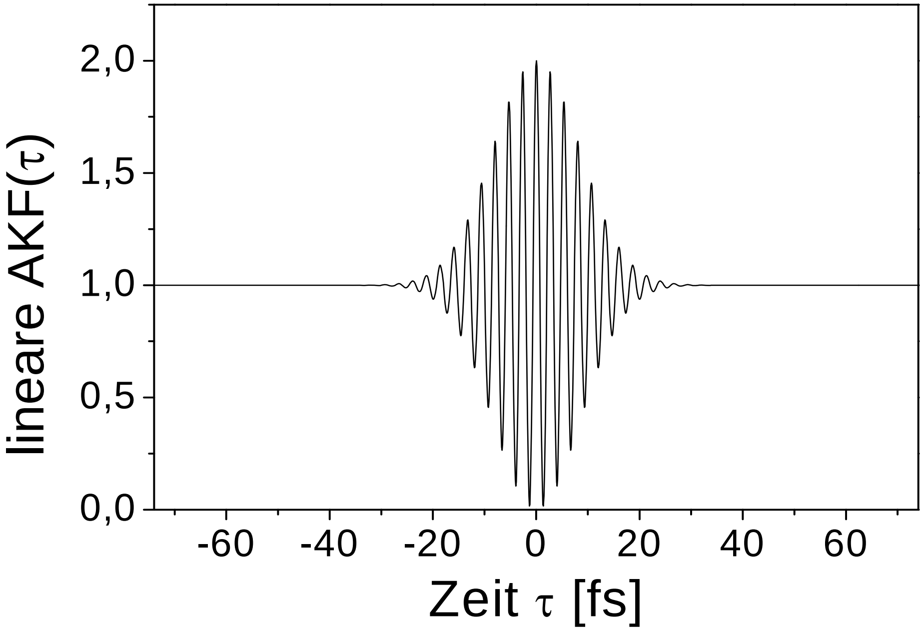
$$S_{quad}(\tau) = \int_{-\infty}^{\infty} \{E(t) + E(t+\tau)\}^4 \, dt$$

Linear autocorrelation

$$S_{linear}(\tau) = \int_{-\infty}^{\infty} \{E(t) + E(t+\tau)\}^2 \, dt$$

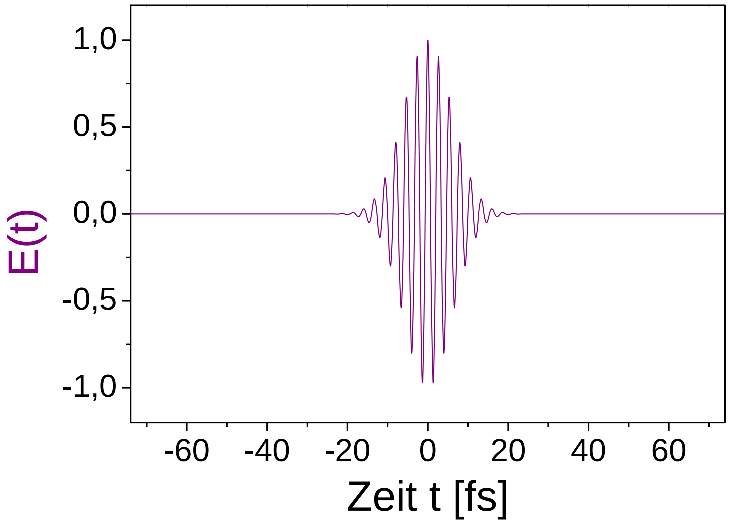
$$= 2\int_{-\infty}^{\infty} E^2(t)\, dt + 2\int_{-\infty}^{\infty} E(t)E(t+\tau)\, dt$$

$$\frac{S_{linear}(0)}{S_{linear}(\infty)} = \frac{4I_0}{2I_0} = 2$$

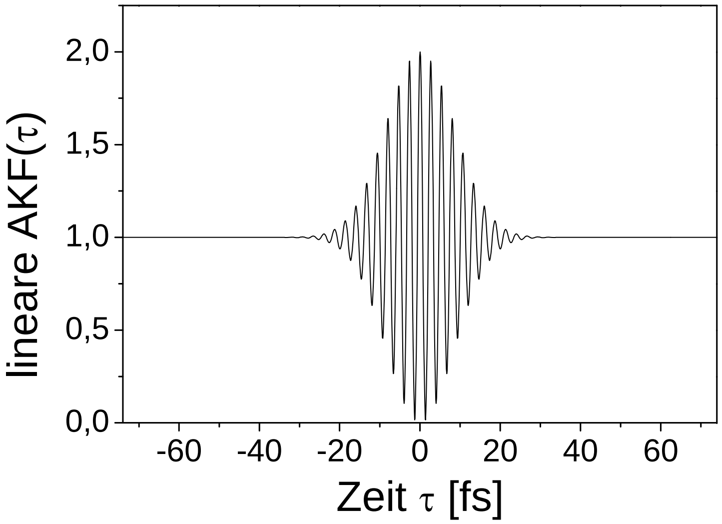


Linear autocorrelation of a bandwidth limited pulse

10 fs bandwidth limited

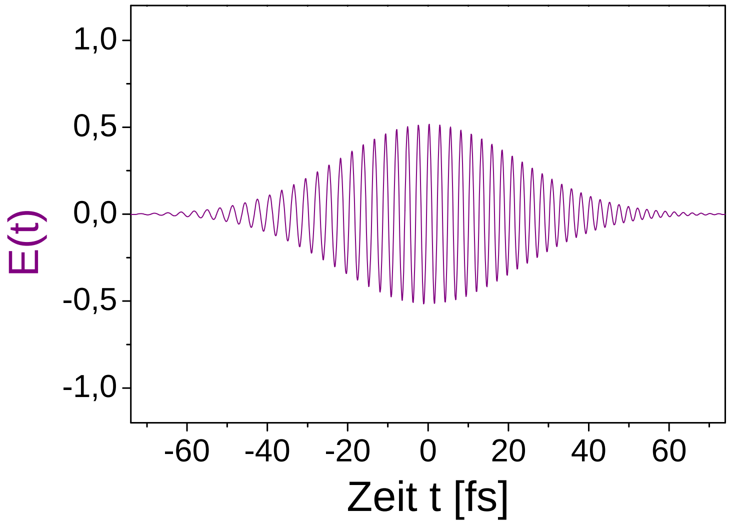


Linear autocorrelation

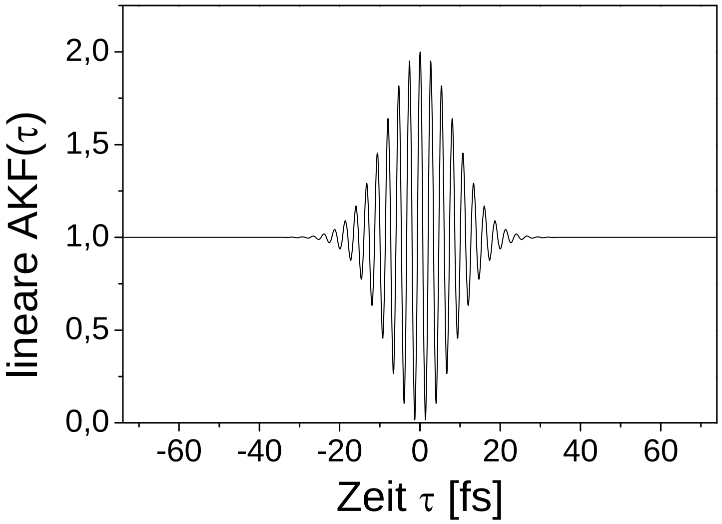


Linear autocorrelation of a chirped pulse

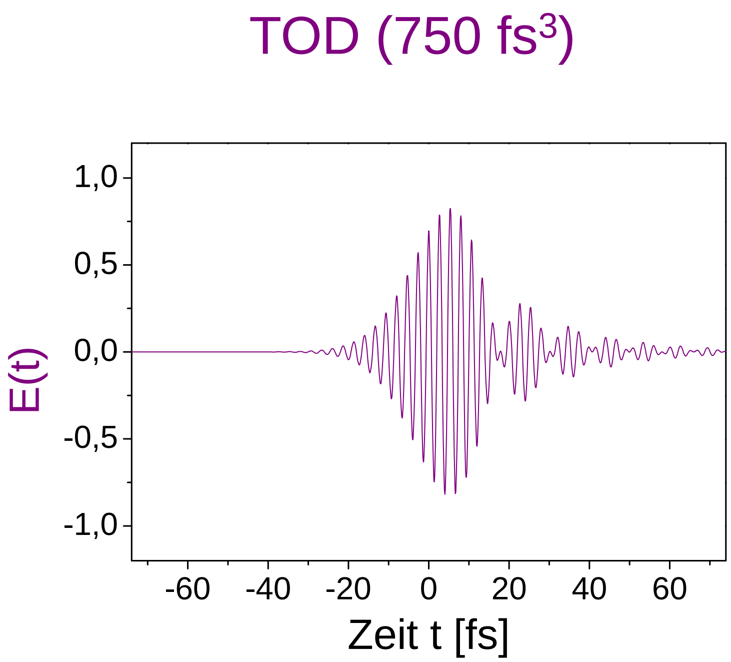
Linear chirp (130 fs²)

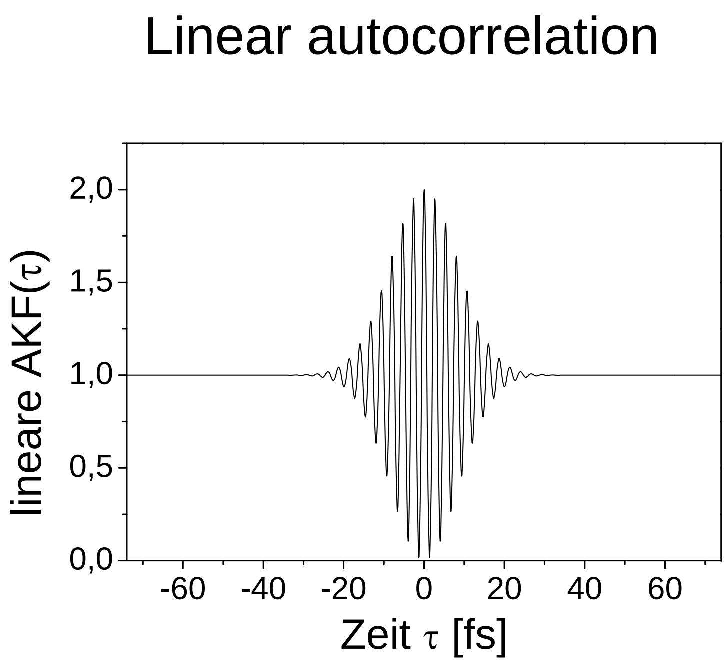


Linear autocorrelation



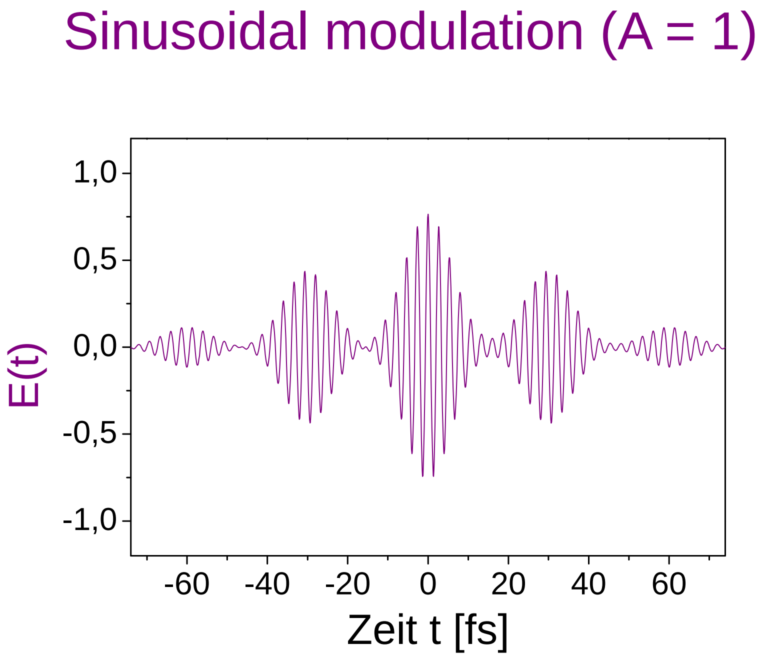
Linear autocorrelation of a TOD pulse

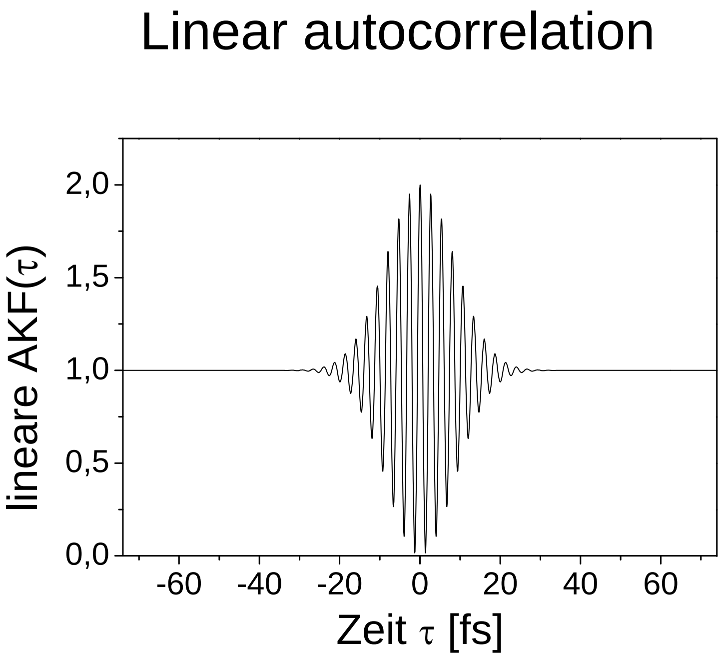




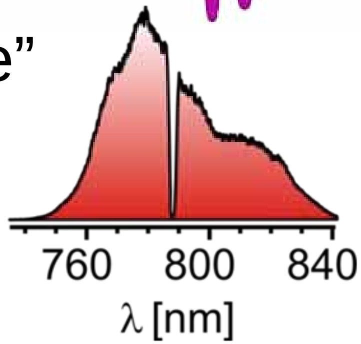
The linear autocorrelation function is always *gerade*!

Linear autocorrelation of a sinusoidally modulated pulse

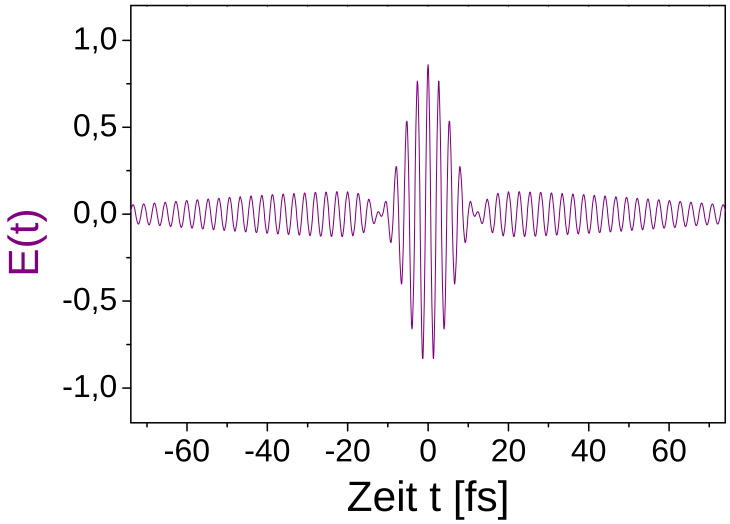




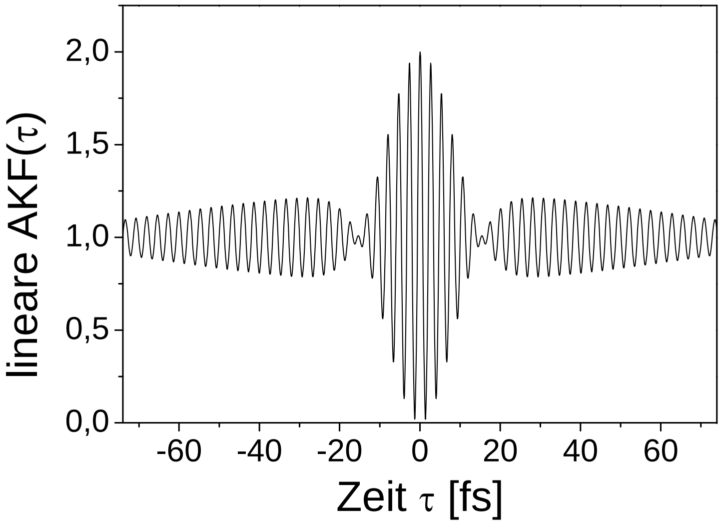
Linear autocorrelation of a "spectral hole"



„Spectral hole"



Linear autocorrelation

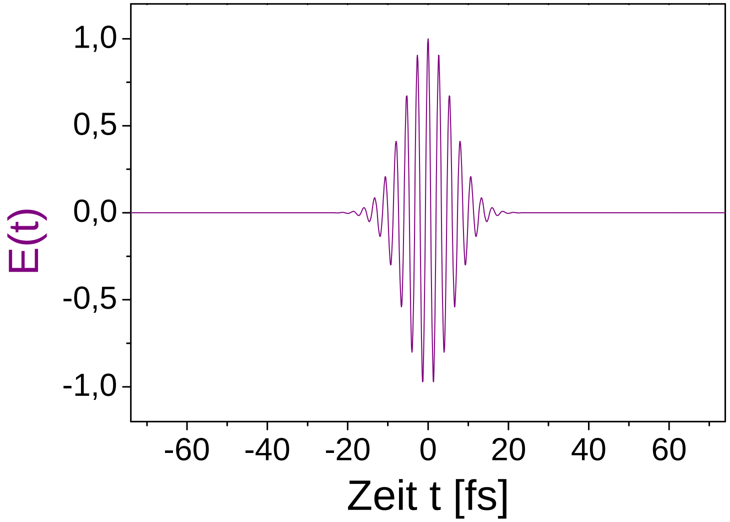


Appl. Phys. Lett., ***87***, *121113 (2005)*

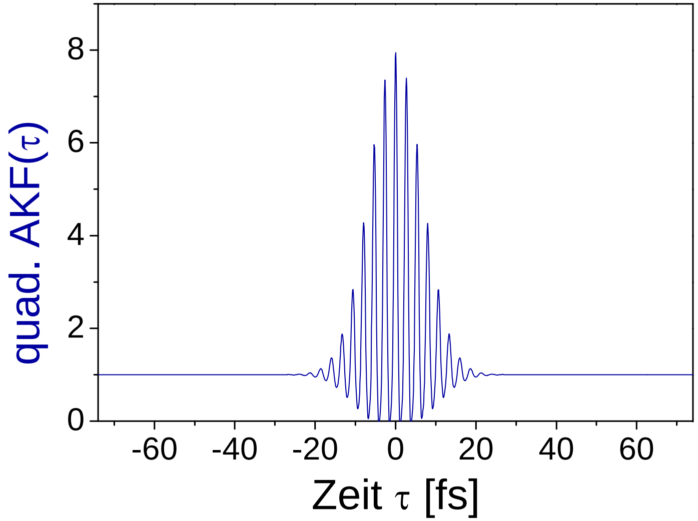
2^{nd} order autocorrelation of a bandwidth limited pulse

$$S_{quad}(\tau) = \int_{-\infty}^{\infty} \{E(t) + E(t+\tau)\}^4 \, dt$$

10 fs bandwidth limited

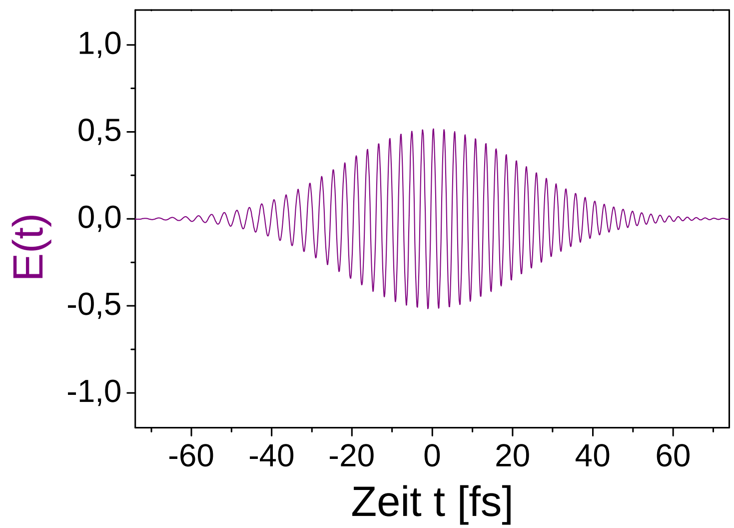


2^{nd} order autocorrelation

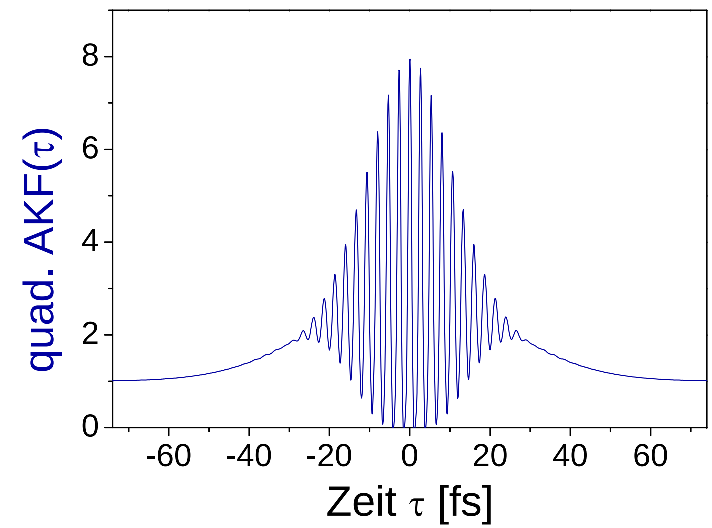


2nd order autocorrelation of a chirped pulse

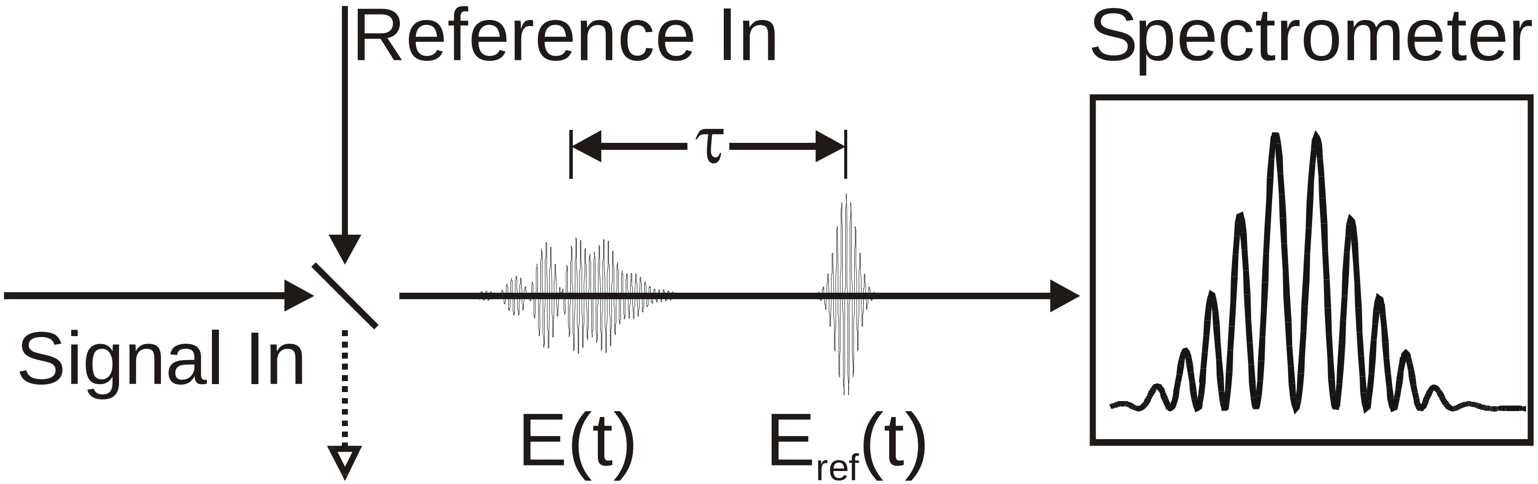
Linear chirp (130 fs²)



2nd order autocorrelation



Spectral interference



Spectral interference

$$E_2(t) = E_{mod}(t) + E(t+\tau)$$

$$\tilde{E}_2(\omega) = \tilde{E}_{mod}(\omega) + \tilde{E}(\omega)e^{i\omega\tau}$$

$$= \tilde{E}(\omega)e^{-i\varphi(\omega)} + \tilde{E}(\omega)e^{i\omega\tau}$$

$$\boxed{PSD_2(\omega) = 2\left\{1 + \cos[\omega\tau + \varphi(\omega)]\right\} PSD(\omega)}$$

Power Spectral Density $PSD = |\tilde{E}(\omega)|^2$

SI of an up-chirp

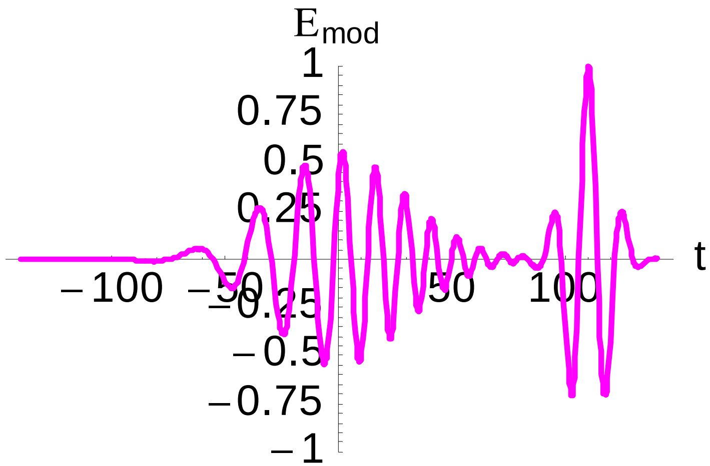
$$E_2(t) = E_{mod}(t) + E(t+\tau)$$

$$\varphi(\omega) = \frac{\varphi_2}{2}\omega^2$$

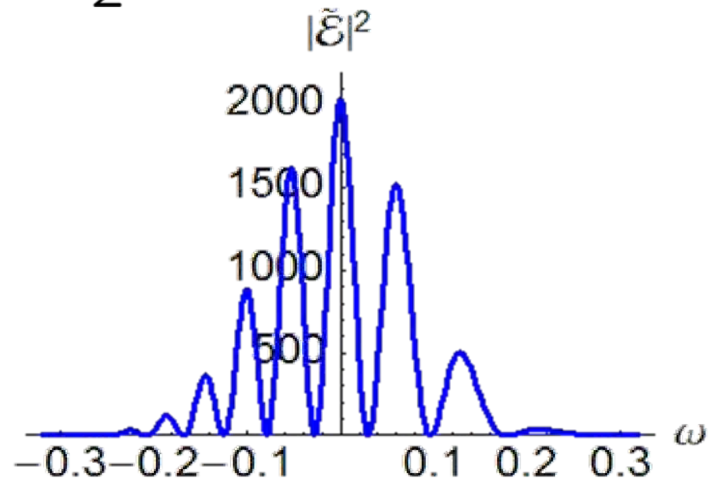
$$\varphi_2 = 250\text{fs}^2$$

$$\Delta t = 15\text{fs}$$

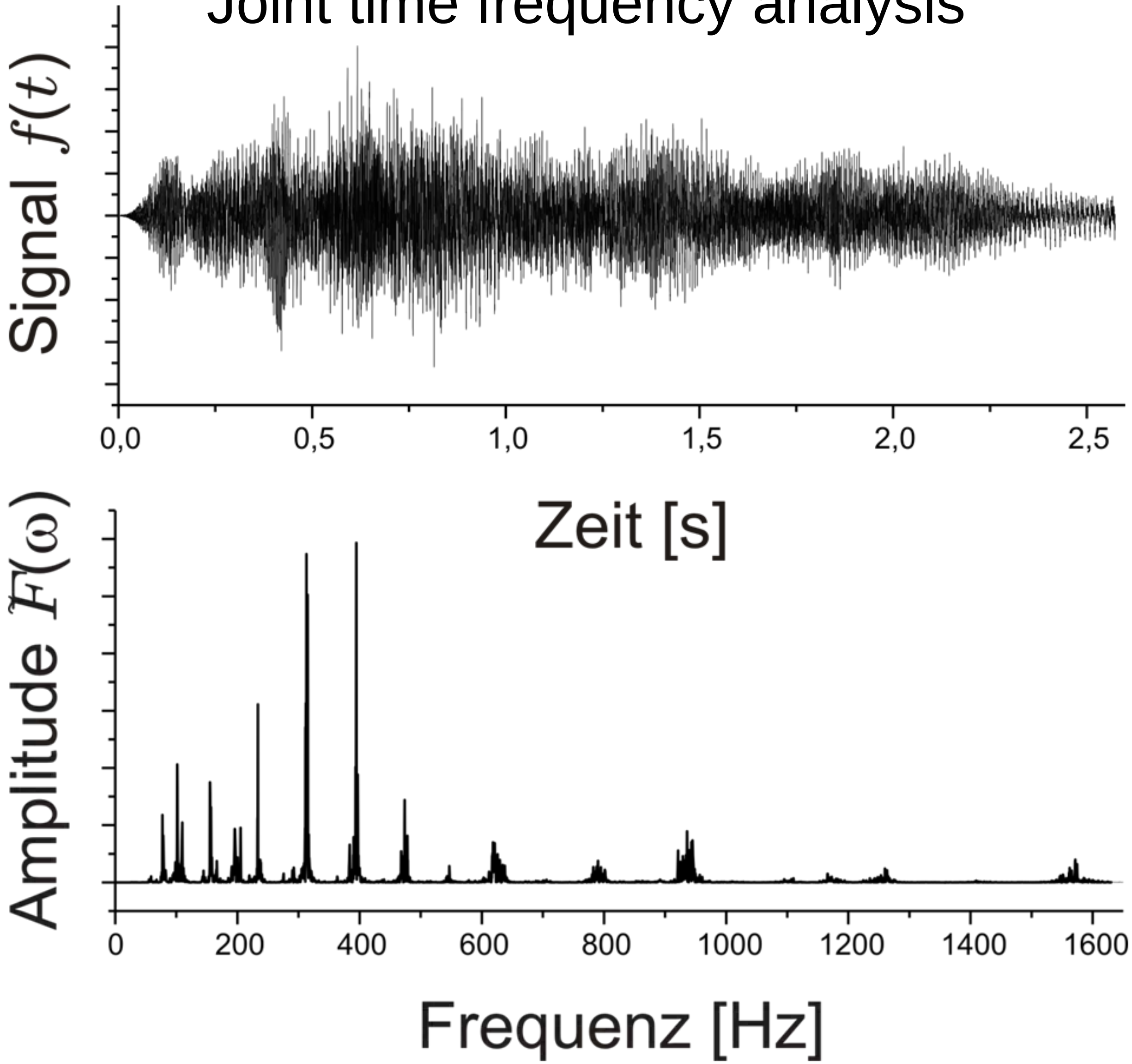
$$\tau = -110\text{fs}$$



$$PSD_2(\omega) = 2PSD(\omega)\left\{1 + \cos[\omega\tau + \frac{\varphi_2}{2}\cdot\omega^2]\right\}$$



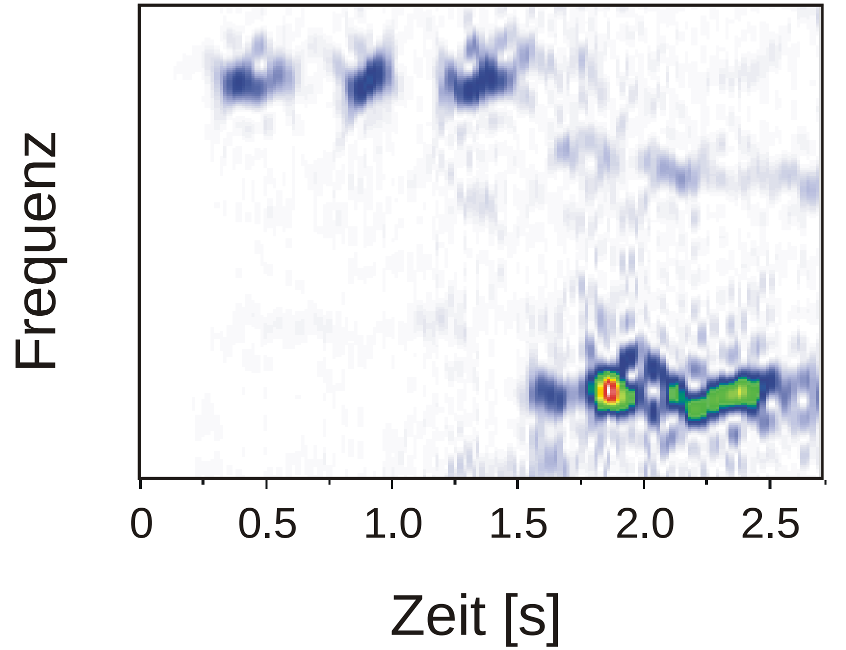
Joint time frequency analysis



A spectrogram

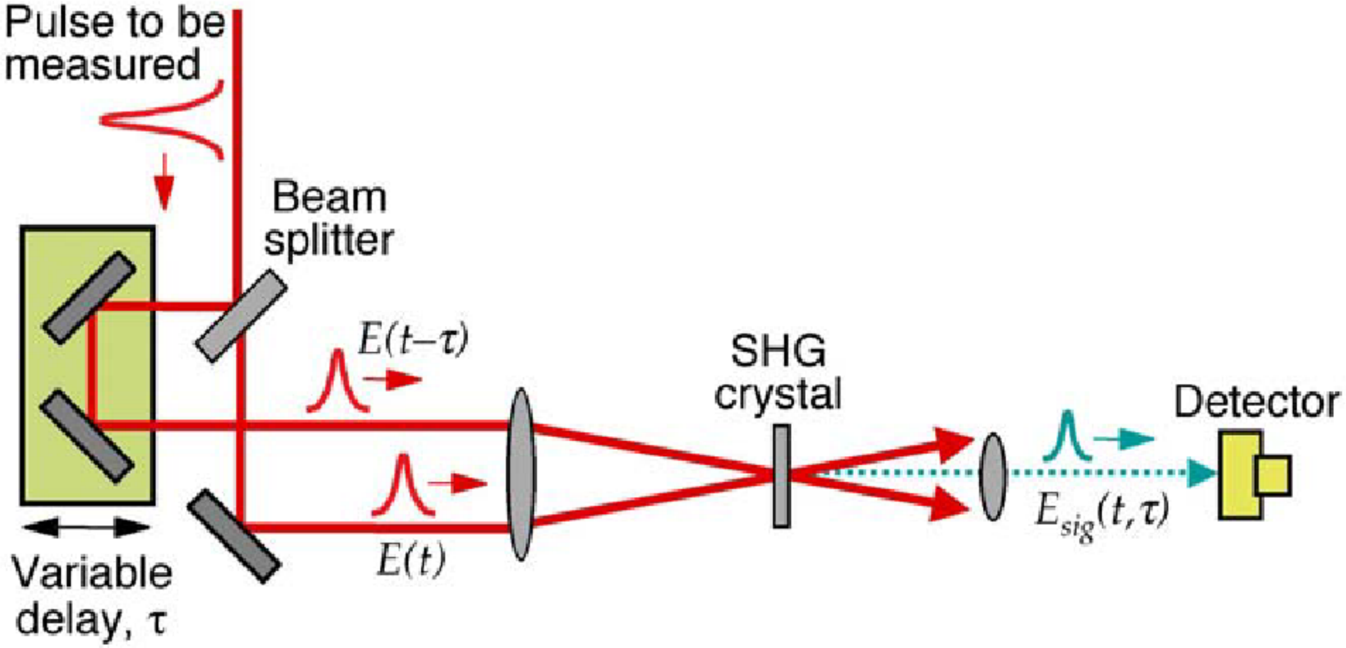
Ludwig van Beethoven

Symphony No. 5
C minor op. 67
Allegro con brio



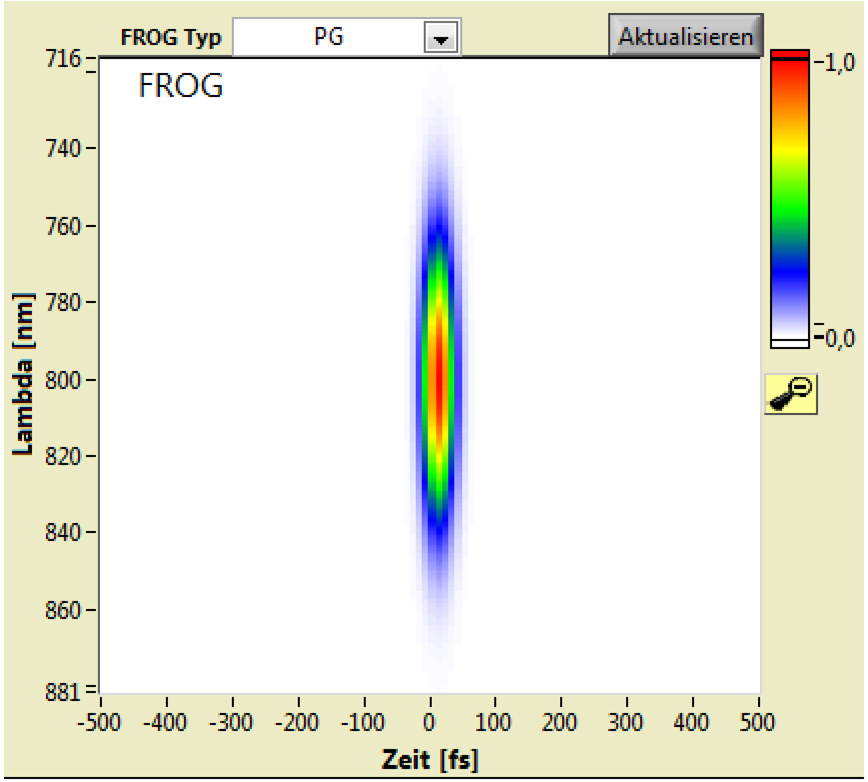
JTFA in optics: FROG

FROG = Frequency Resolved Optical Gating



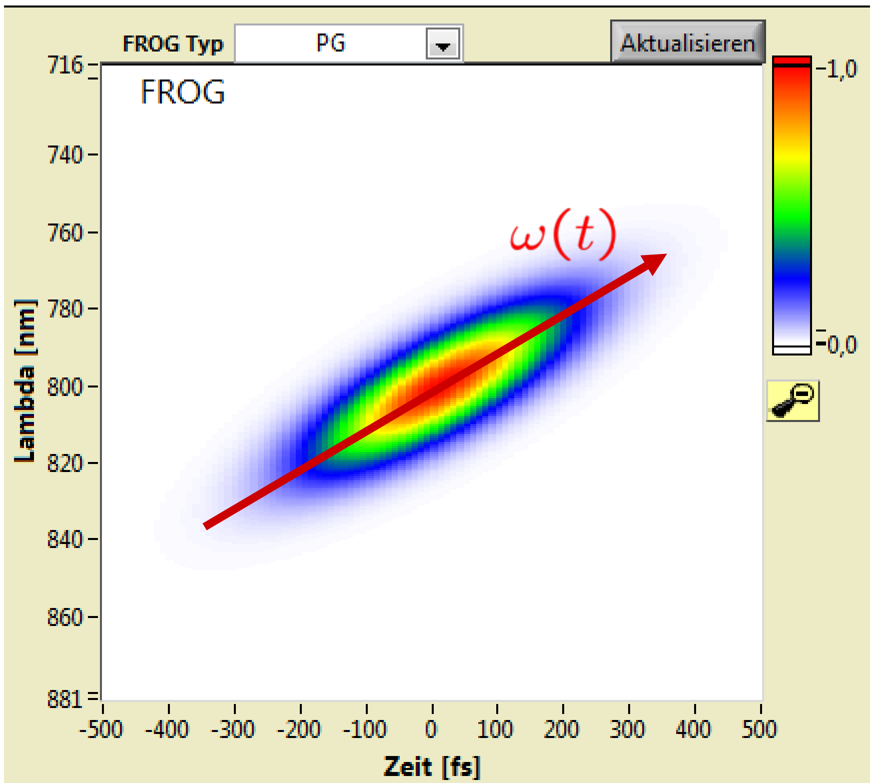
PG FROG of a bandwidth limited pulse

$$I_{Frog}^{PG}(\omega,\tau) = \left| \int_{-\infty}^{\infty} \mathcal{E}(t) |\mathcal{E}(t-\tau)|^2 e^{i\omega t} dt \right|^2$$

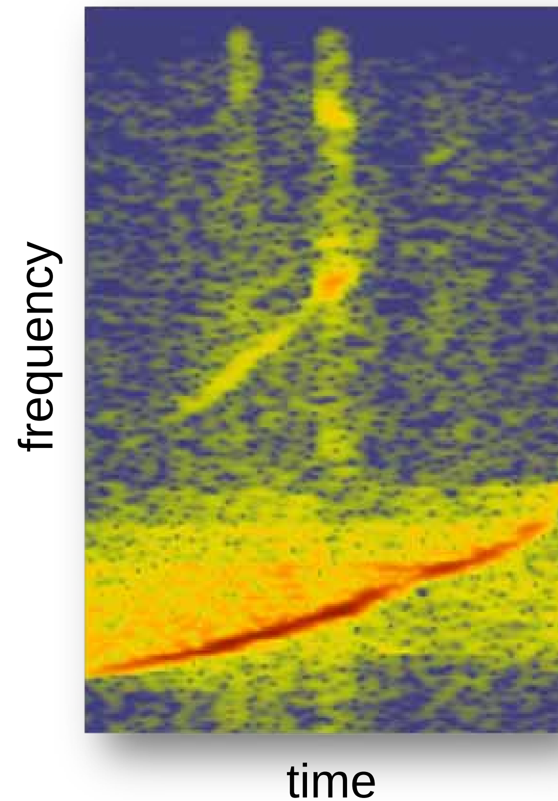


PG FROG of a chirped pulse

$$I^{PG}_{Frog}(\omega,\tau) = \left| \int_{-\infty}^{\infty} \mathcal{E}(t) |\mathcal{E}(t-\tau)|^2 e^{i\omega t} dt \right|^2$$

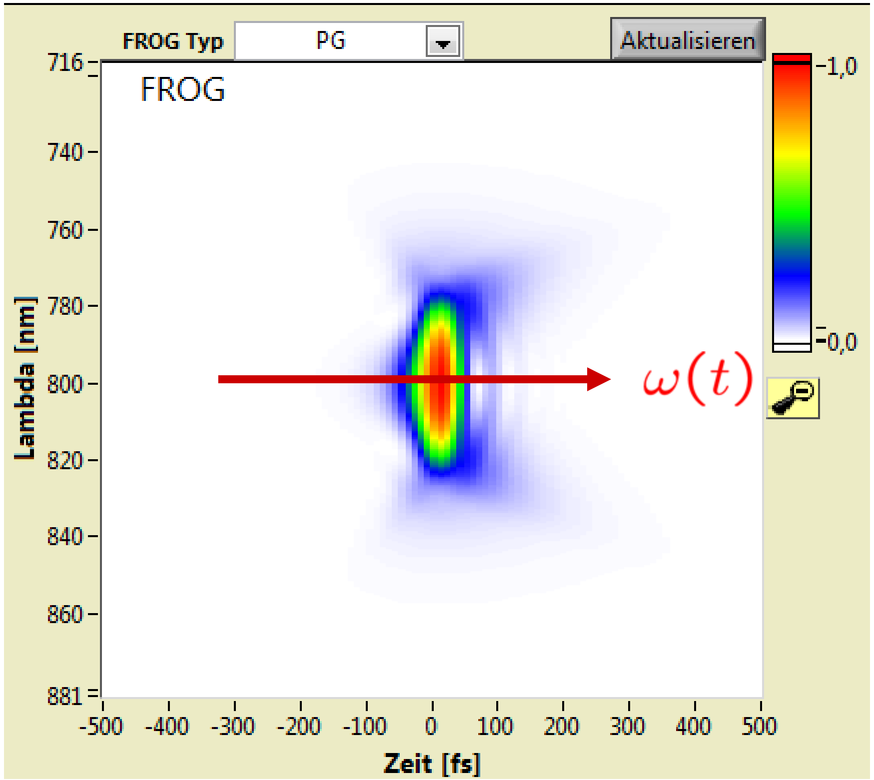


Spectrogram

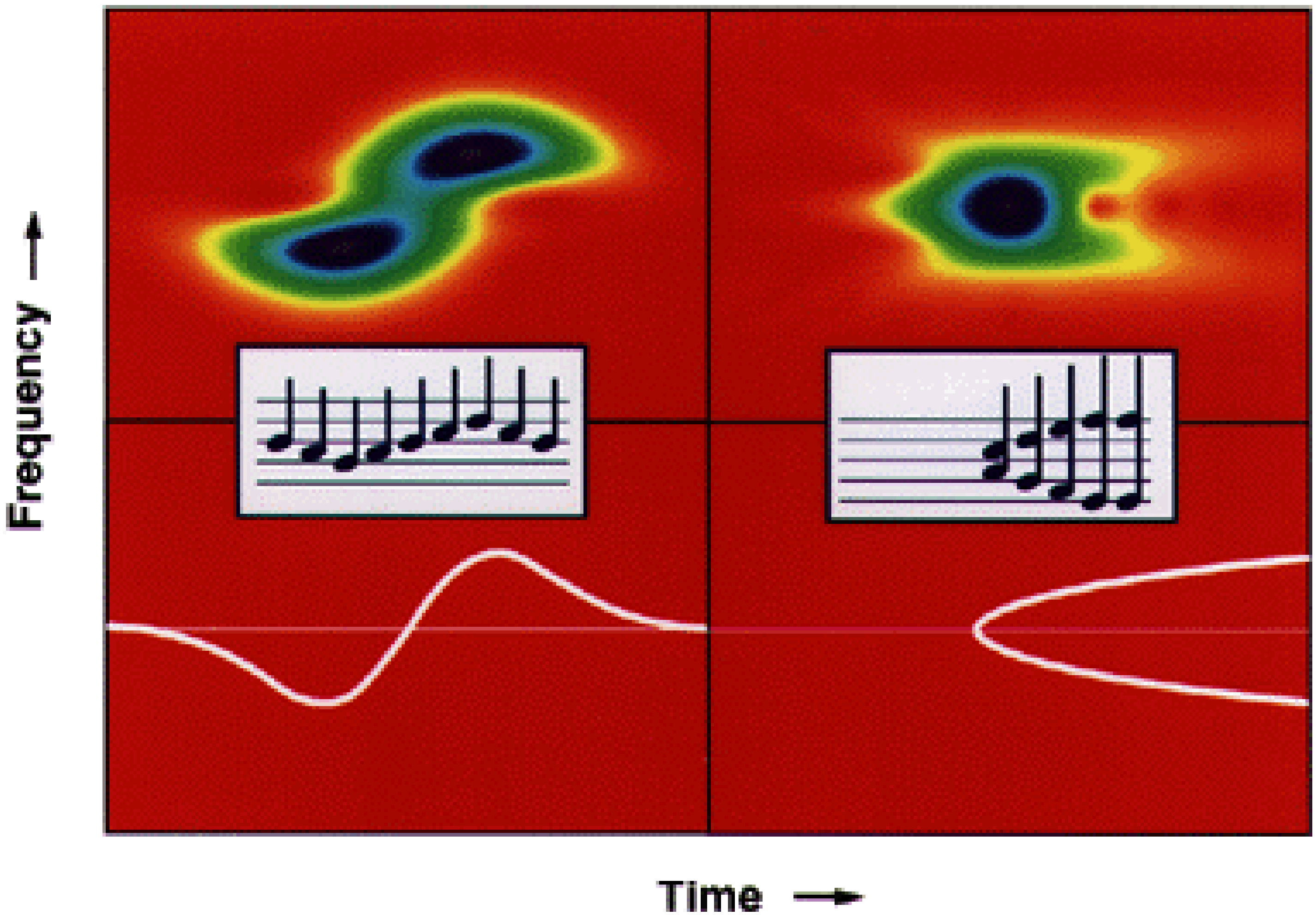


PG FROG of a TOD pulse

$$I_{Frog}^{PG}(\omega,\tau) = \left| \int_{-\infty}^{\infty} \mathcal{E}(t) |\mathcal{E}(t-\tau)|^2 e^{i\omega t} dt \right|^2$$

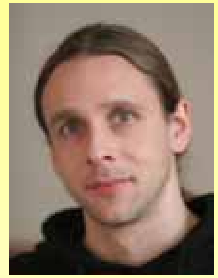


Analogy to music




Prof. Dr. T. Baumert


PD Dr. M. Wollenhaupt

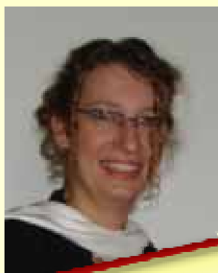

T. Bayer


L. Englert

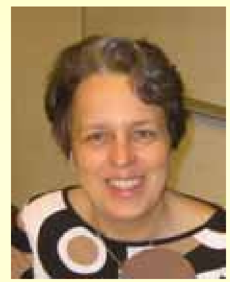

L. Haag


C. Horn


P. Kasper



PHD positions available


U. Meier-Diedrich


J. Mildner


C. Sarpe

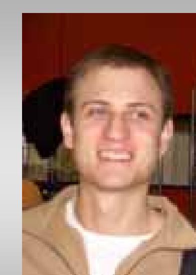

J. Schneider


M. Winter


PD Dr. A. Assion


R. Bäumner


Dr. D. Liese


Dr. A. Präkelt